Ozone Episode
Southern Lake Michigan Region
20 - 25 June 2002

An Analysis
of
Ozone and Meteorological Measurements
Aloft and at the Surface

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May 2003

Background to the Analysis

- June 21-24, 2002 (Fri. – Mon.): A total of 30 site-day exceedances of the ozone 1-hour national ambient air quality standard(NAAQS, 124 ppb) were measured at several near-shore monitoring sites in the southern Lake Michigan area (Fig. 1). This was the worst ozone episode in the region since the 1990's. Exceedances of the 1-hr ozone NAAQS during this episode at certain sites in Wis, Illinois & Indiana halted these states' requests to the US EPA to redesignate to attainment of the 1-hr ozone NAAQS.

- June 22-25, 2002: A Wis DNR airplane flew up to 4 separate 2 hr+ monitoring flights per day over southern Lake Michigan (Figs. 2 & 3: flight A: approx. 0400-0700 CST, B: approx. 0830-1130 CST, C: approx. 1200-1430 CST, D: approx. 1600-1840 CST). Actual flight times varied slightly. Not all days witnessed all 4 flights.

- Measurements of ozone, temperature, relative humidity, wind speed, wind direction & other parameters were taken during the WDNR monitoring flights.

Background to the Analysis (continued)

- June 22-25, 2002: Daily, a contractor airplane (RB Jacko & Assoc.) completed one round trip monitoring flight between Lafayette, IN and La Crosse WI -- collecting ozone and other measurements inland south and west of L. Michigan (i.e., L. Mich. “boundary” flight) during approx. 11:00-16:00 CST (Figs. 4 & 5)
- Routine land surface-based ozone and meteorological monitoring observations were also collected during this episode by the state air monitoring programs in Wisconsin, Illinois, Indiana and Michigan.
- The following slides:
  - Depict graphical (time-height) analyses of the WDNR and RB Jacko aircraft-measured data (10 second ave.) collected during 22-25 June 02.
  - Depict graphical (mostly in time series) analyses of land-based data.
  - From these graphs -- present land-based weather and ozone (both temporally & spatially) in context to aloft O3 and meteorological fields.
  - Drawing upon previous research on L. Michigan ozone meteorology (summarized in a conceptual model [Appendix A]) -- attempt to establish some cause-effect relationships between the meteorology and ozone, particularly between aloft over the Lake and on land.

Figure 1

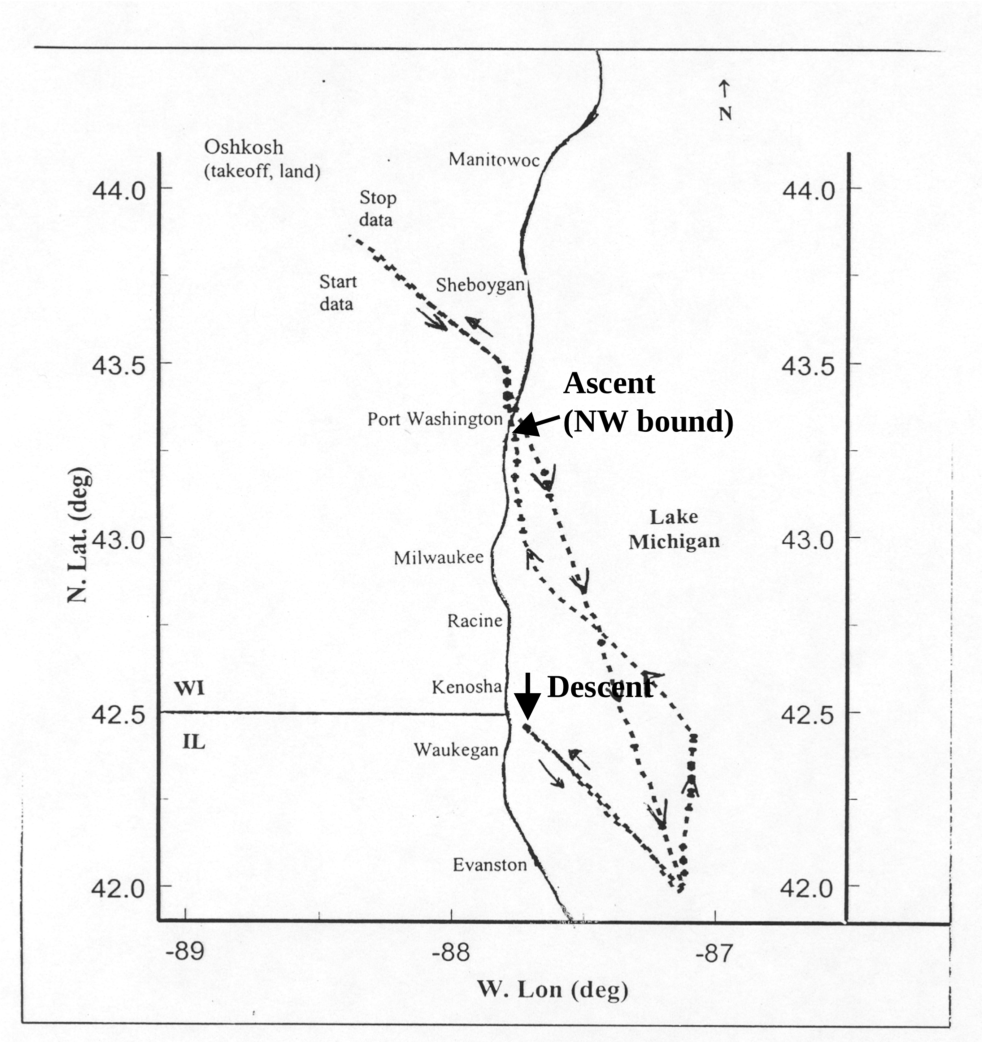
General Study Area
Surface Sites Analyzed
Ozone Episode
20 – 25 June 02 (Thur – Tues)

Analyzed Parameters

- **Ozone (aloft & surface)**
- **Temperature (aloft & surface)**
- **Wind Speed (aloft & surface)**
- **Wind Direction (aloft & surface)**
- **Relative humidity (aloft only)**

Figure 2

WDNR Air Monitoring Airplane Flight Path
Two-Dimensional (Lat-Lon) Depiction
During 22 - 25 June 02



The WDNR monitoring airplane flew up to 4 separate 2 hr+ flights per day over southern Lake Michigan.
Flight A: Approx. 0400-0700 CST,
B: Approx. 0830-1130 CST,
C: Approx. 1200-1430CST,
D: Approx. 600-1840 CST.

Actual flight times varied slightly. Not all days witnessed all 4 flights. Measurements of ozone, temperature, relative humidity, wind speed, wind direction & other parameters were continuously taken during these flights.

Figure 3

WDNR Air Monitoring Airplane Flight Path
Three-Dimensional Depiction
(Lat-Lon-Ht Above L. Mich Surface Level)
During 22 - 25 June 02

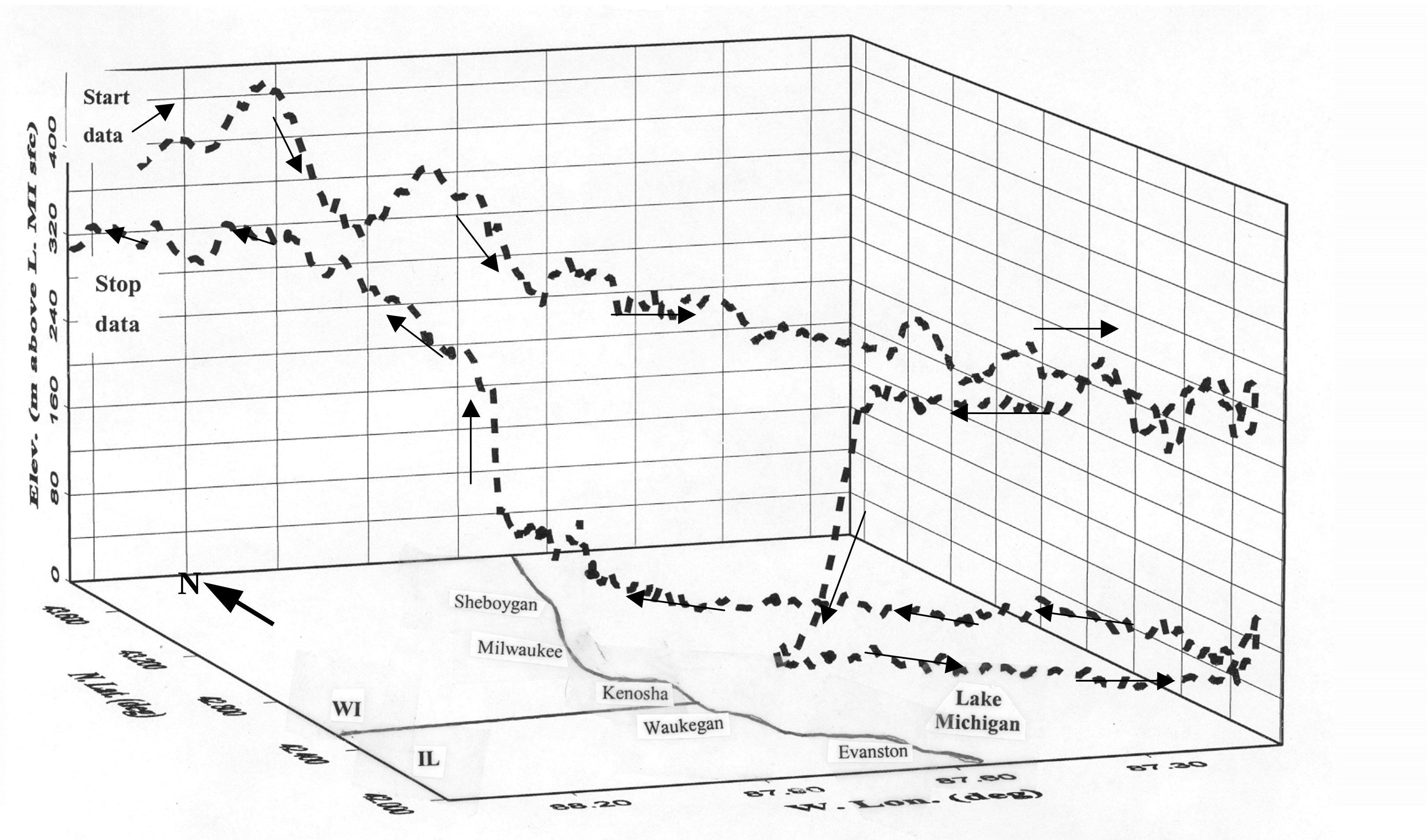


Figure 4

RB Jacko L. Mich. “Boundary” Monitoring Flight Path

2-Dimensional (Lat.-Lon.) Depiction

The RB Jacko airplane completed one of these flights per day -- continuously measuring ozone and other parameters.

Leave Lafayette, IN in late morning (CST)
Turnaround above La Crosse, WI 2 hrs+ later
Return (same path), Arrive Lafayette 2 hrs+ later

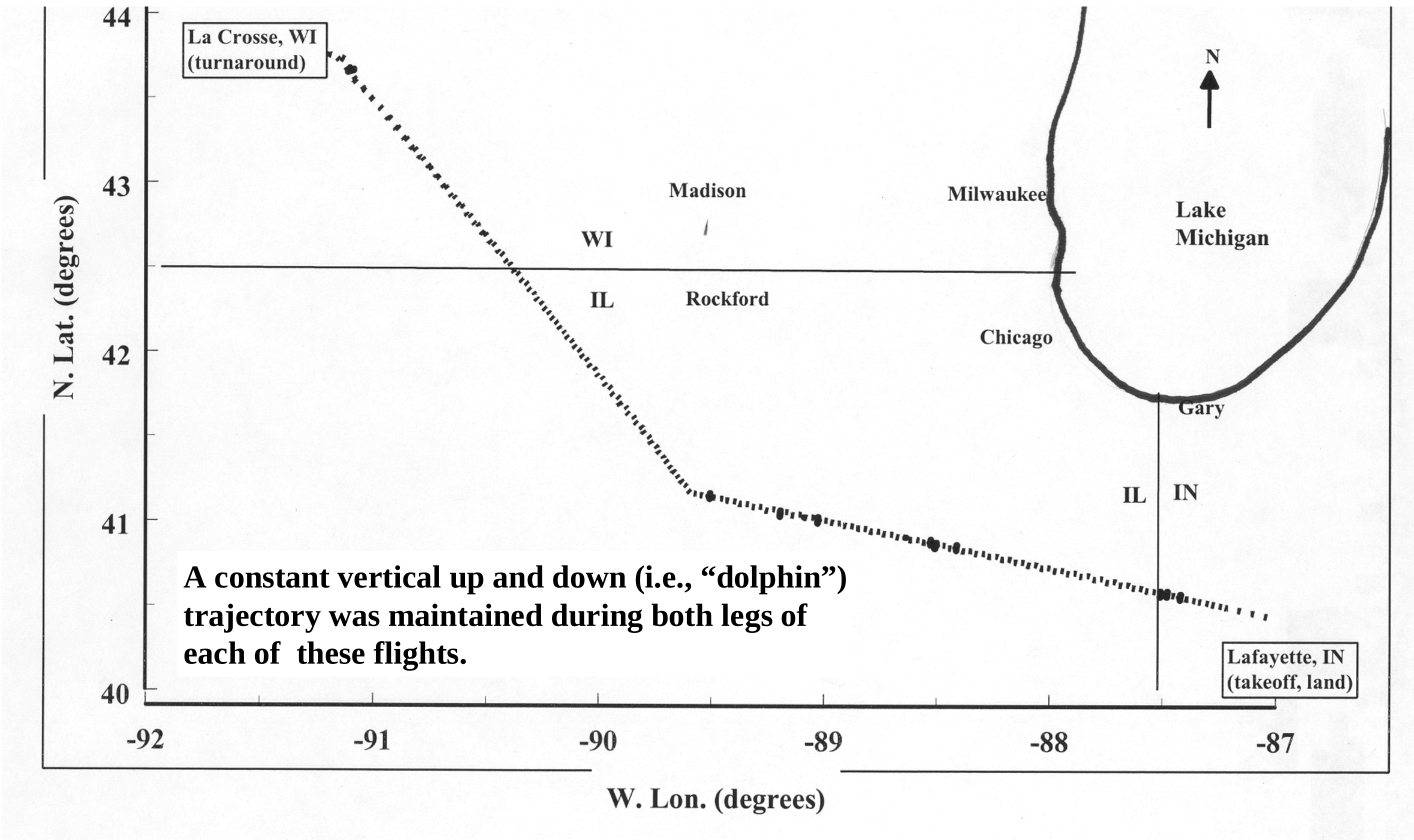
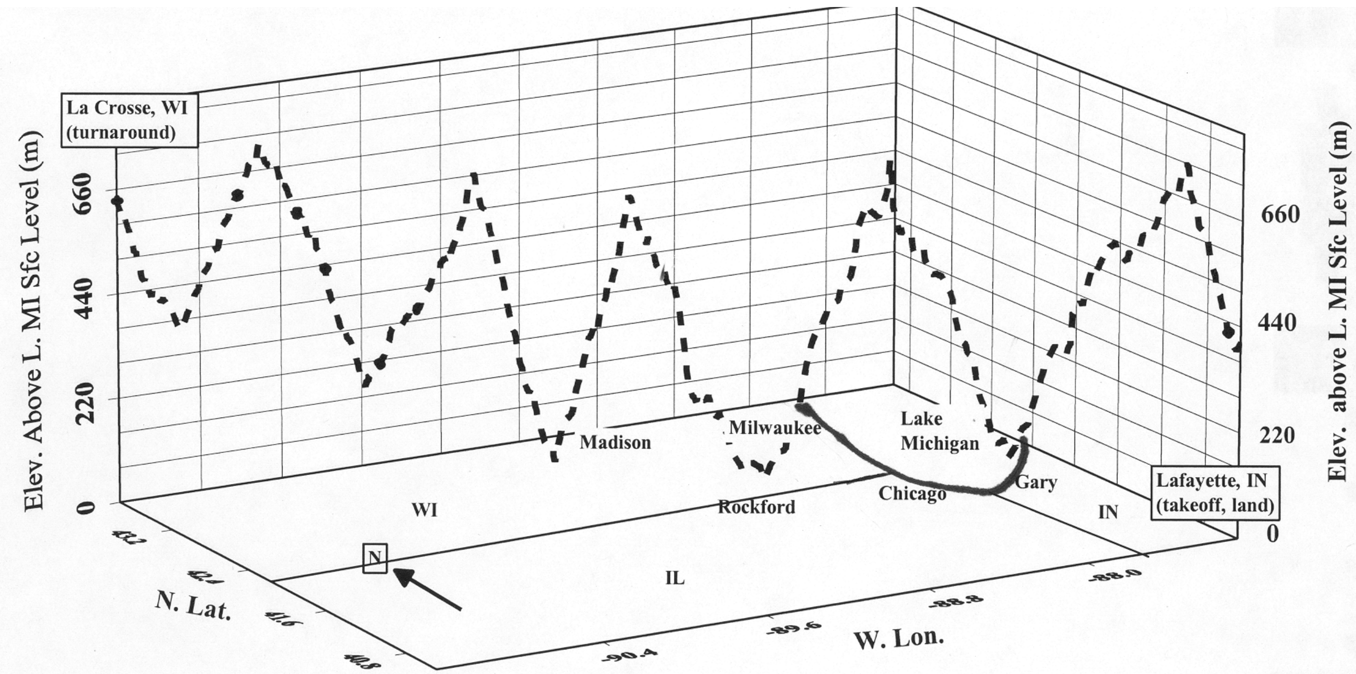


Figure 5

RB Jacko L. Mich. "Boundary" Monitoring Flight Path
Typical 3-Dimensional (Lat.-Lon-Elevation) Depiction

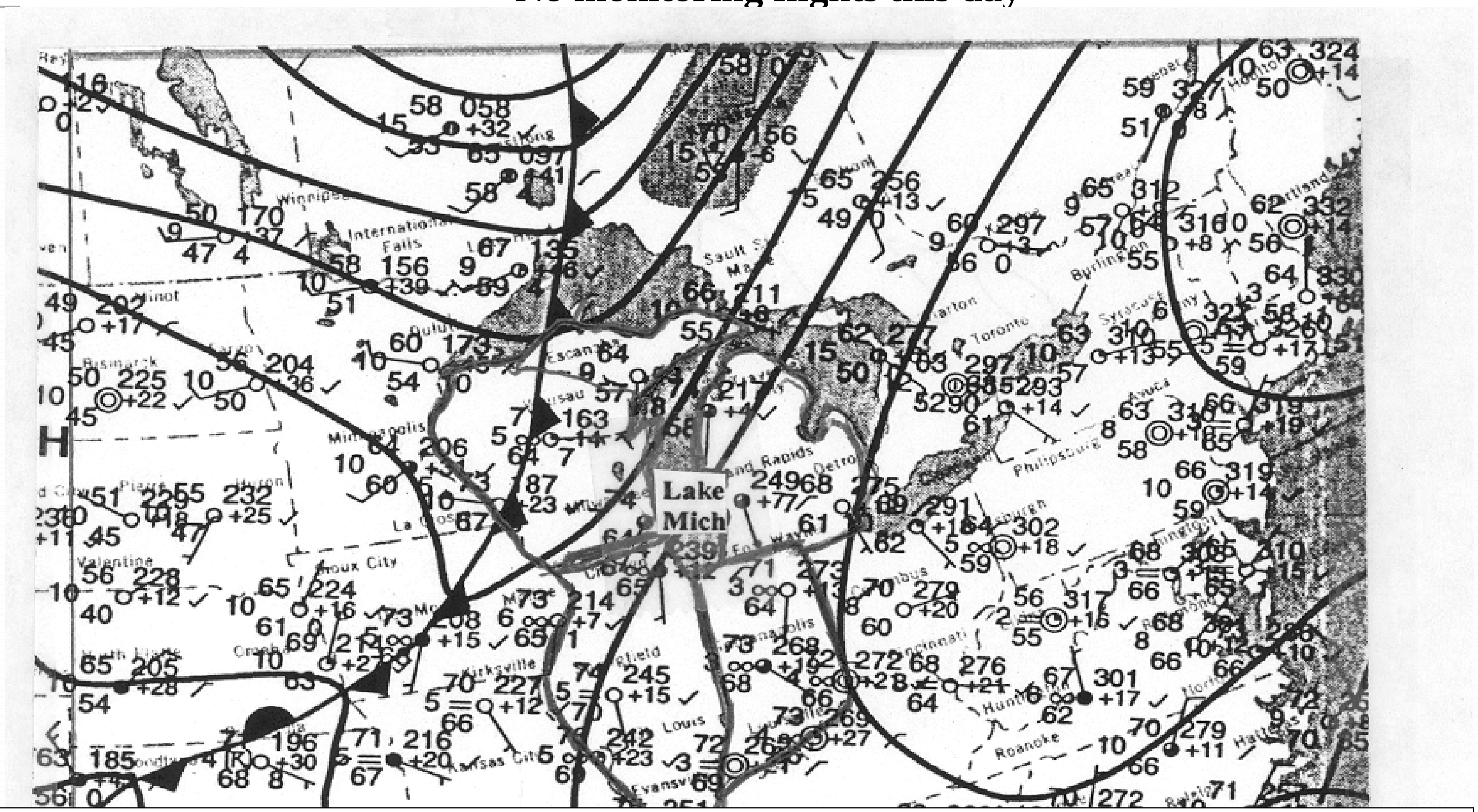
Leave Lafayette, IN in late morning (CST)
Turnaround above La Crosse, WI 2 hrs+ later
Return (same path), Arrive Lafayette 2 hrs+ later



A constant vertical up and down (i.e., "dolphin") trajectory was maintained during both legs of each of these flights.

Figure 6

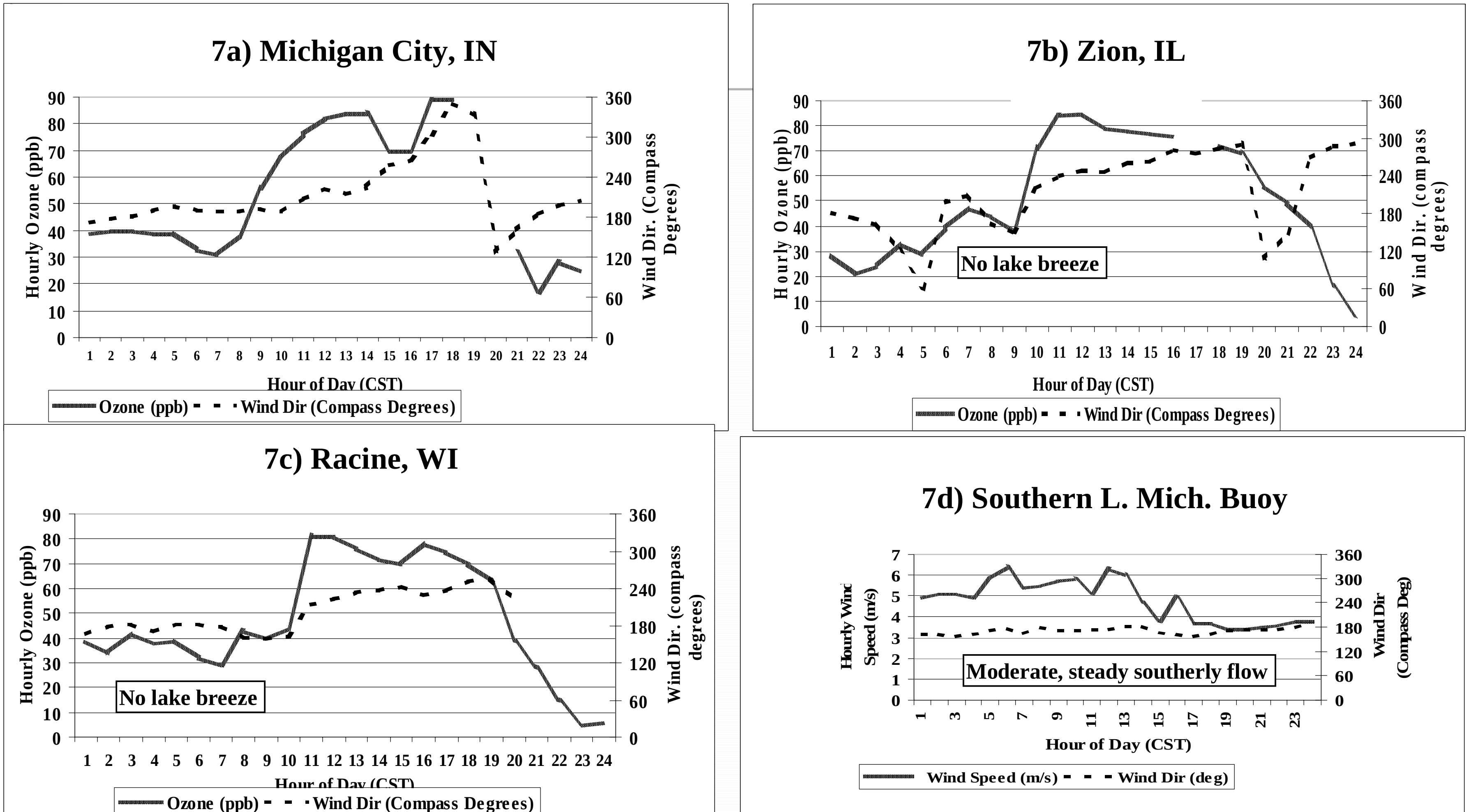
Surface Synoptic Weather Map
6 AM CST 20 June 02
(Thur -- "Ramp Up" Day to Episode)
No monitoring flights this day



<u>6/20/02 Lake Mich. area surface synoptic meteorology:</u> Relatively warm (to 25 C) and humid (dew point temperatures to 20 C) largely due to generally southerly flow directed by a high pressure system centered in Maine. Most of the L. Michigan region saw extensive cloud coverage and occasional rain due to and ahead of an advancing north/south-oriented cold front. However, western Mich (too far east of the cold front's influence) had cloudless, but hazy skies for most of day.

Figure 7: Time Series - Hrly Surface Data - 20 June 02

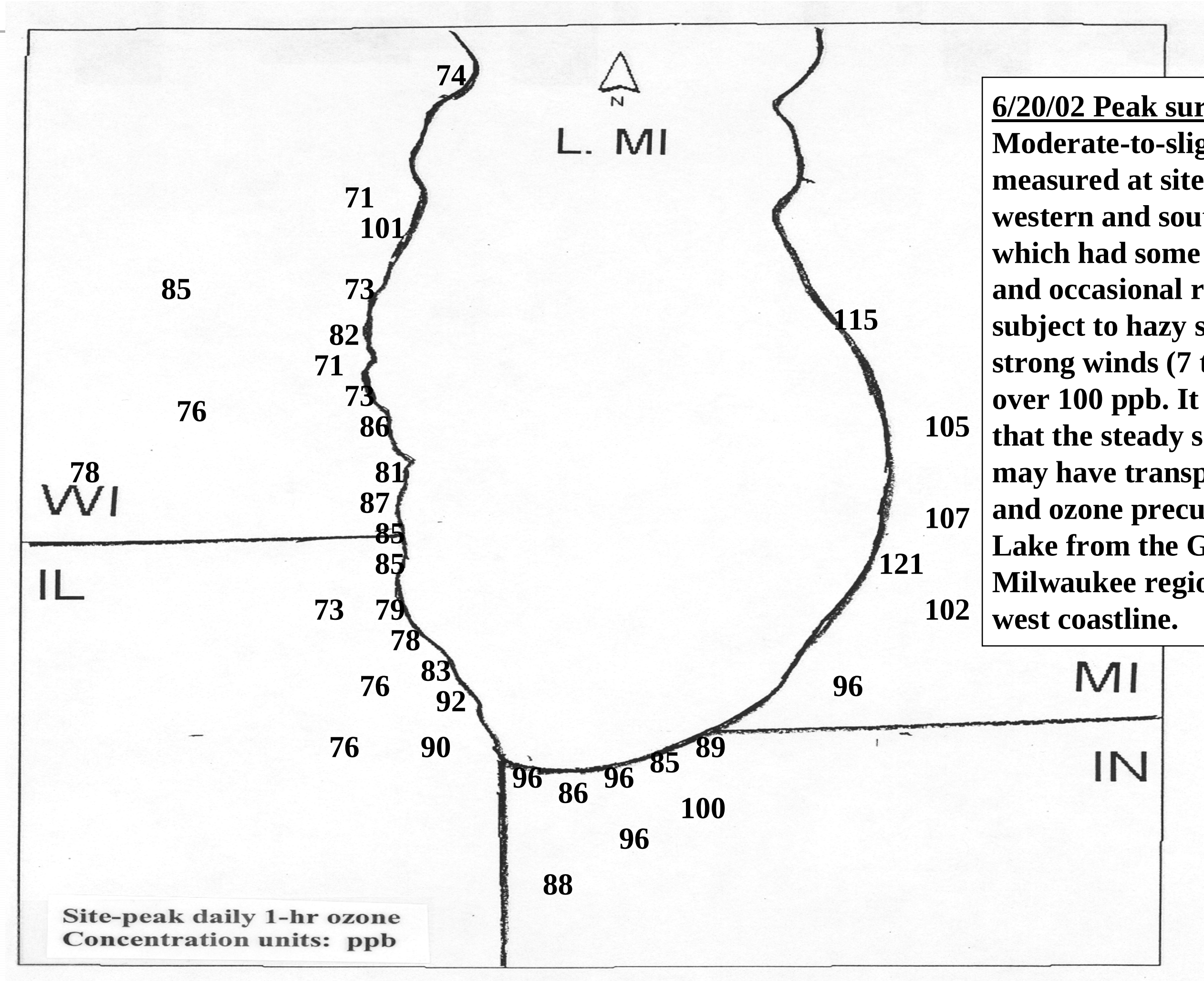
A) Mich. City, IN, B) Zion, IL & C) Racine, WI: Ozone & Wind Dir
D) Southern L. Mich. Buoy: Wind Speed & Direction



<u>6/20/02 surface</u>: **These shoreline ozone / wind sites witnessed moderately high ozone (peaks: 90 ppb) and predominately west-southwesterly flow during the mid-day hours. After sunset the ozone levels dropped to near zero -- due to both a lack of sunlight and insufficient amounts of precursors available to sustain photochemical production of ozone to replace that destroyed at the surface. The mid-Lake buoy saw moderate (4-6 m/s) southerly winds -- suggesting influence from a high pressure system.**

Figure 8

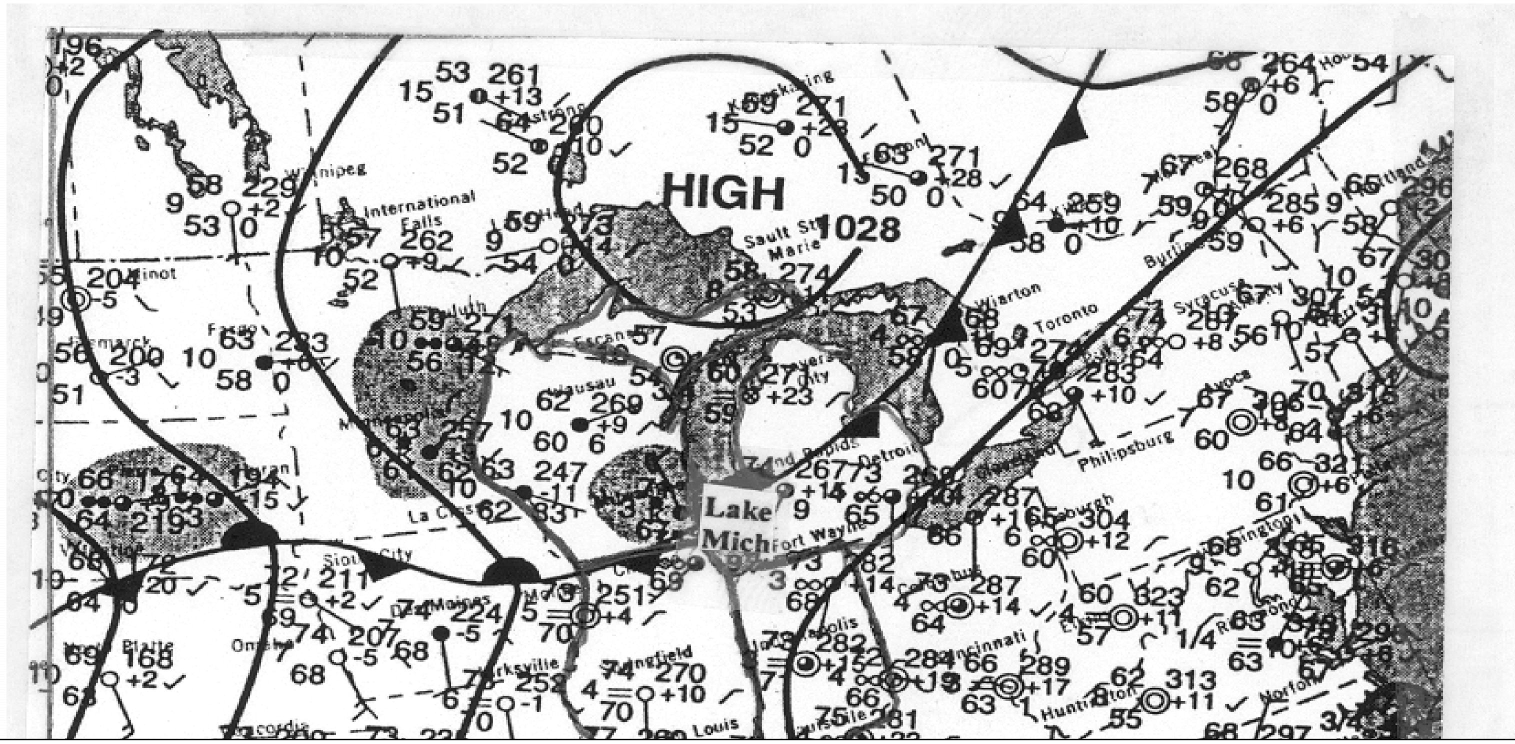
Site Peak-Daily 1-Hr Ozone (ppb)
Monitoring Sites in the S. Lake Mich Area
20 June 02 (Thursday)



6/20/02 Peak surface ozone:
Moderate-to-slightly high ozone was measured at sites along L. Mich's western and southern shoreline, which had some overcast conditions and occasional rain. Western Mich., subject to hazy skies and moderately strong winds (7 to 9 m/s) saw ozone over 100 ppb. It can be speculated that the steady southwesterly winds may have transported some ozone and ozone precursors across the Lake from the Gary-Chicago-Milwaukee region to Michigan's west coastline.

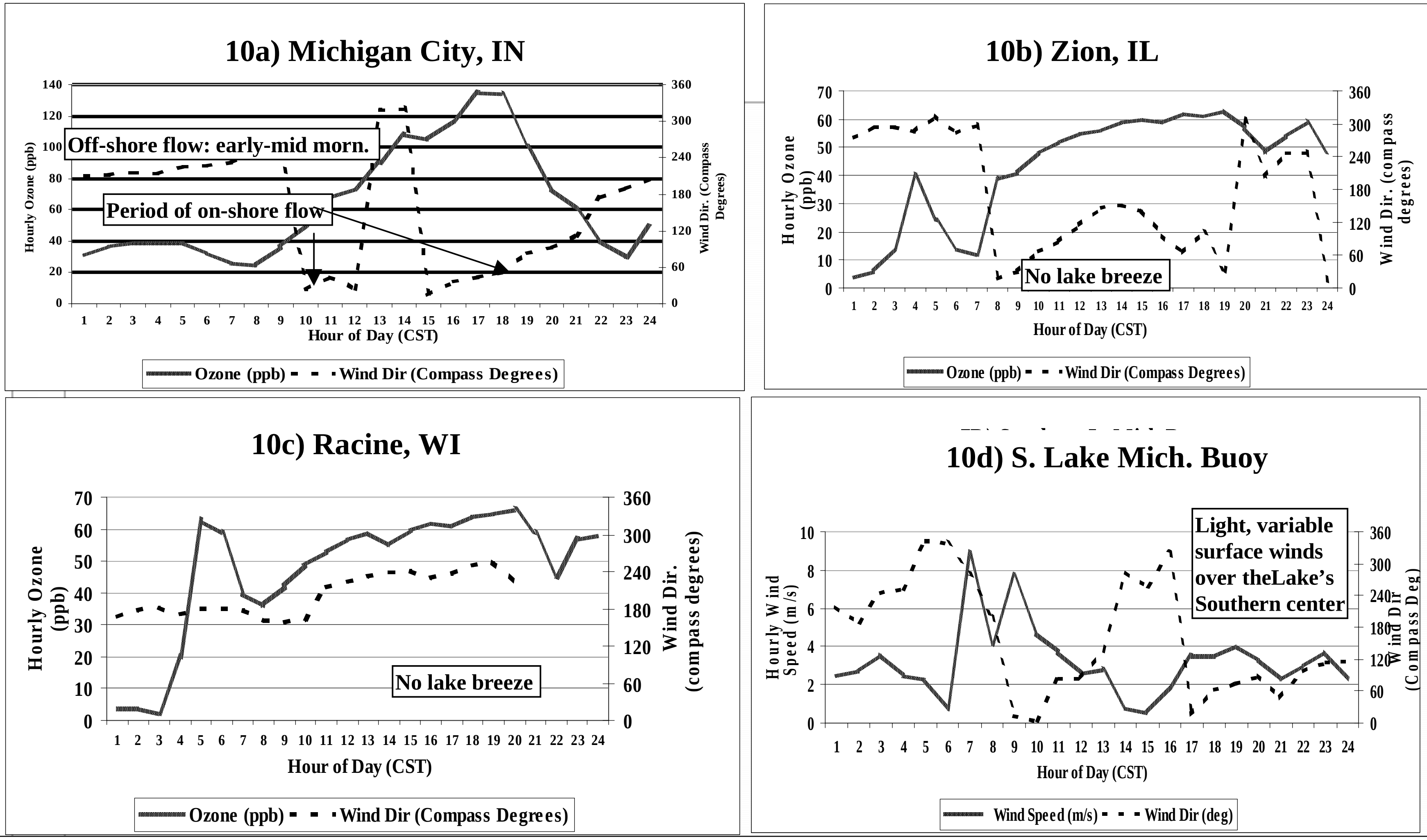
Figure 9

Surface Synoptic Weather Map
6 AM CST 21 June 02
(Friday -- Episode Day 1)
(No monitoring flights this day)



<u>6/21/02 Lake Mich. area surface synoptic meteorology:</u> The front became more east-west oriented, moved into the southern part of the Lake Mich area, gotten wedged in between two surface high pressure systems and began to stall out as a stationary front. The result was that most of the southern L. Mich. area (save for N. Indiana) witnessed considerable convective activity (clouds, rain) due to the front. The extreme southern portion of L. Mich, (including northern Indiana) was spared from the frontal impacts and was under the influence of the surface high pressure (warm, hazy, weak winds with southerly component, subsidence, shallow mixing layer) whose center had migrated to off the coast of New England.

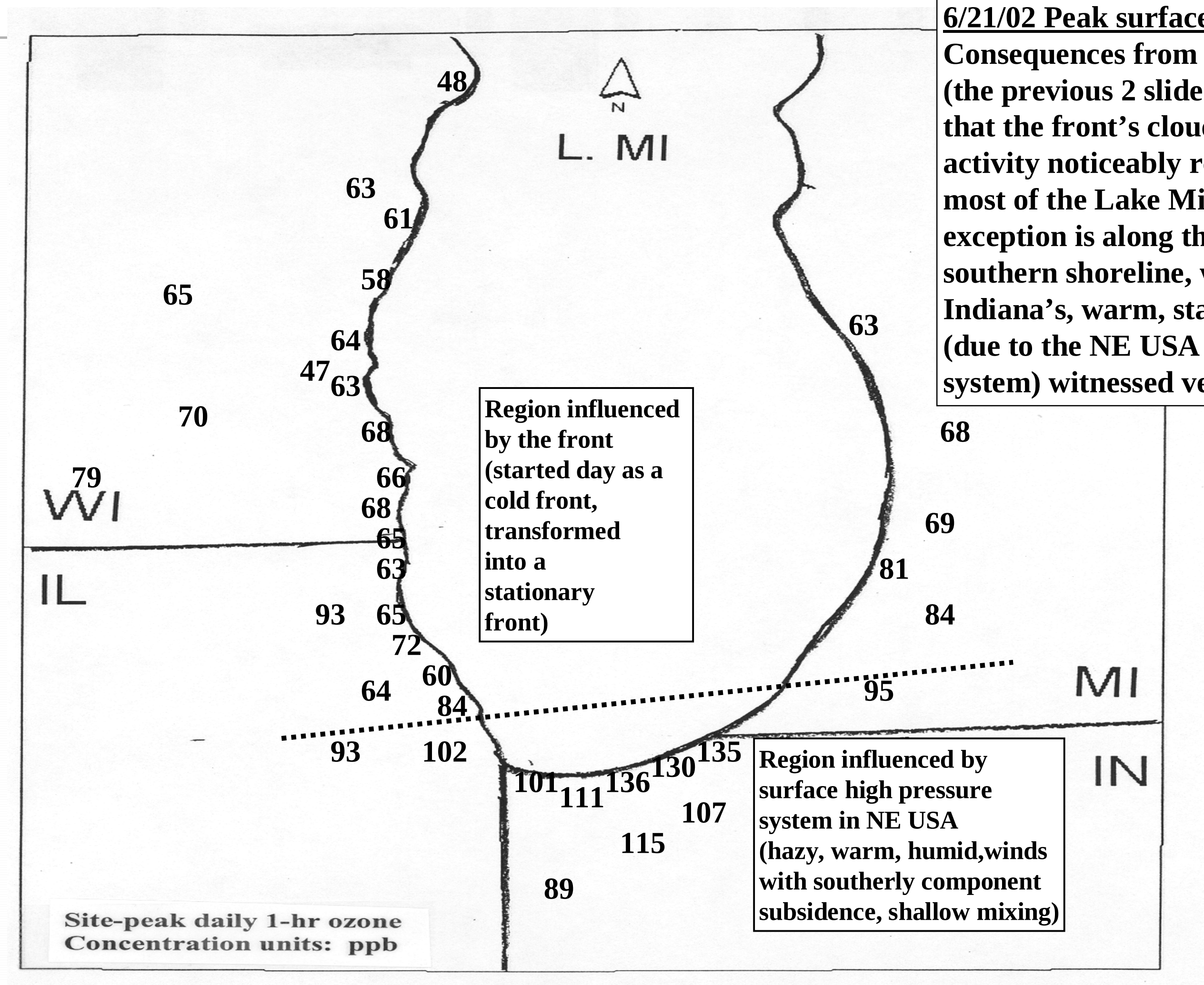
Figure 10: Time Series - Hrly Surface Data - 21 June 02
A) Michigan City, IN, B) Zion, IL & C) Racine, WI: Ozone & Wind Dir, D) Southern L. Mich. Buoy: Wind Speed & Direction



<u>6/21/02 Surface</u>: **Both Zion & Racine, subject to front-related clouds and rain, witnessed modest ozone (peaks: 70 ppb) but noticeably different wind regimes, due to being on opposites of the front (Racine: north, Zion: south until approx. 1900 CST when front passed through). The front stalled out just south of Zion and did not affect Mich. City, which was dominated by high pressure (weak, variable winds, shallow mixing, warm, hazy) that are considered ideal for producing high ozone (peak: 136 ppb). The front, with a wind shift to NW, appeared to pass across the buoy around 0900-1000 CST.**

Figure 11

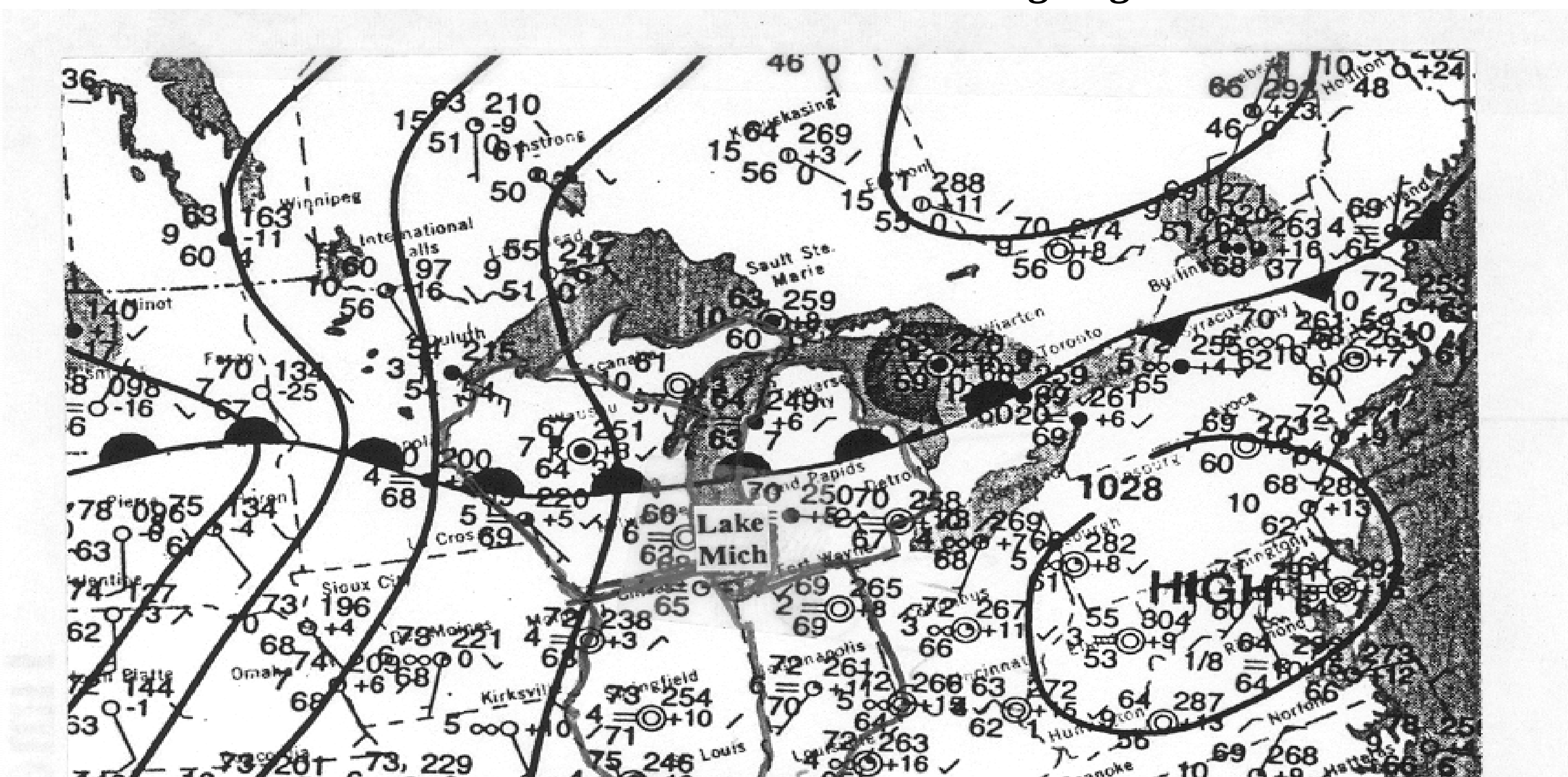
Site Peak-Daily 1-Hr Ozone (ppb)
Monitoring Sites in the S. Lake Mich Area
21 June 02 (Friday)



6/21/02 Peak surface ozone:
Consequences from 6/21's weather (the previous 2 slides), it is evident that the front's cloud and rain activity noticeably reduced ozone in most of the Lake Mich. area. The exception is along the Lake's southern shoreline, where N. Indiana's, warm, stagnant, hazy air (due to the NE USA high pressure system) witnessed very high ozone.

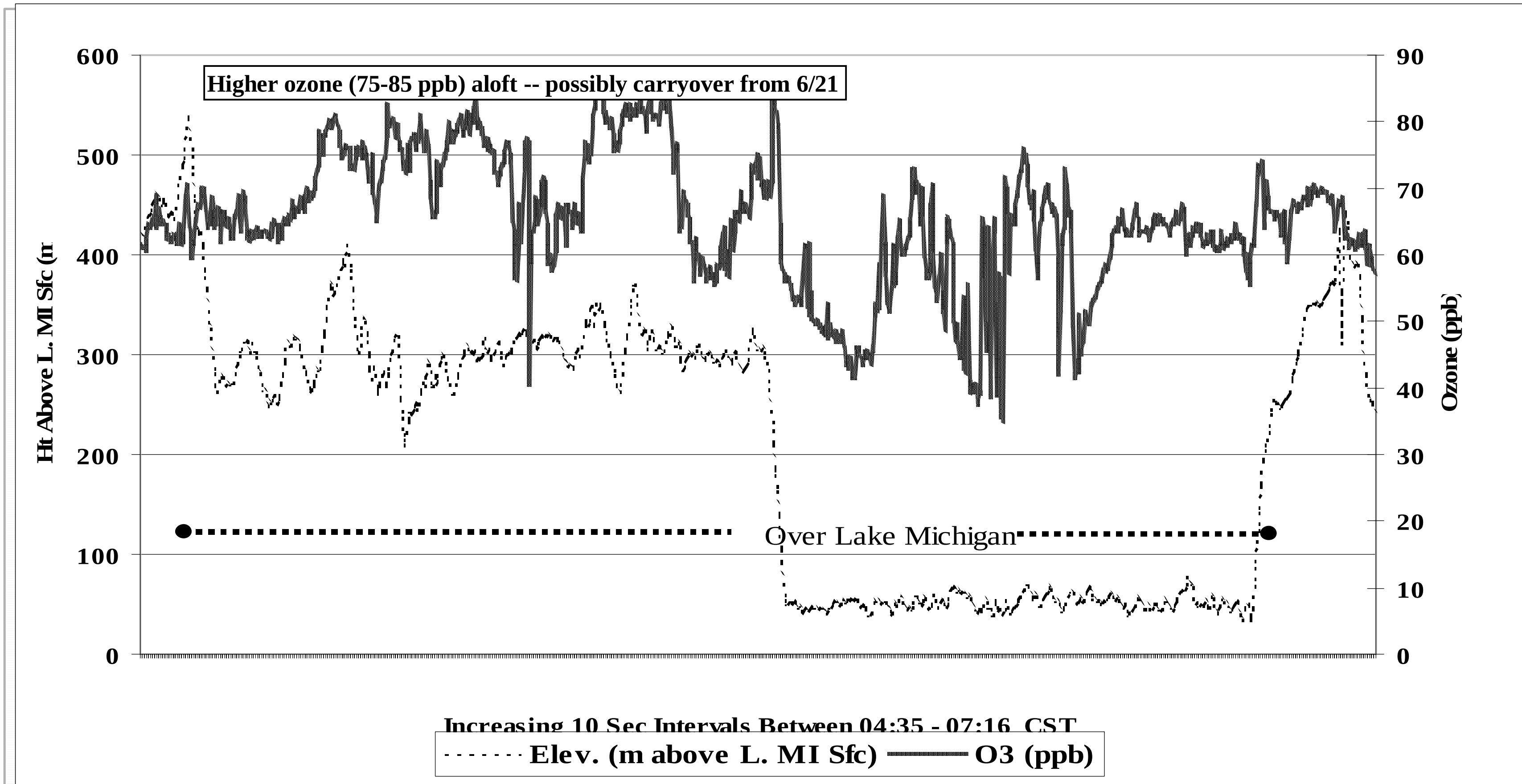
Figure 12

Surface Synoptic Weather Map
6 AM CST 22 June 02
(Saturday -- Episode Day 2)
4 WDNR and 1 RB Jacko Monitoring Flights



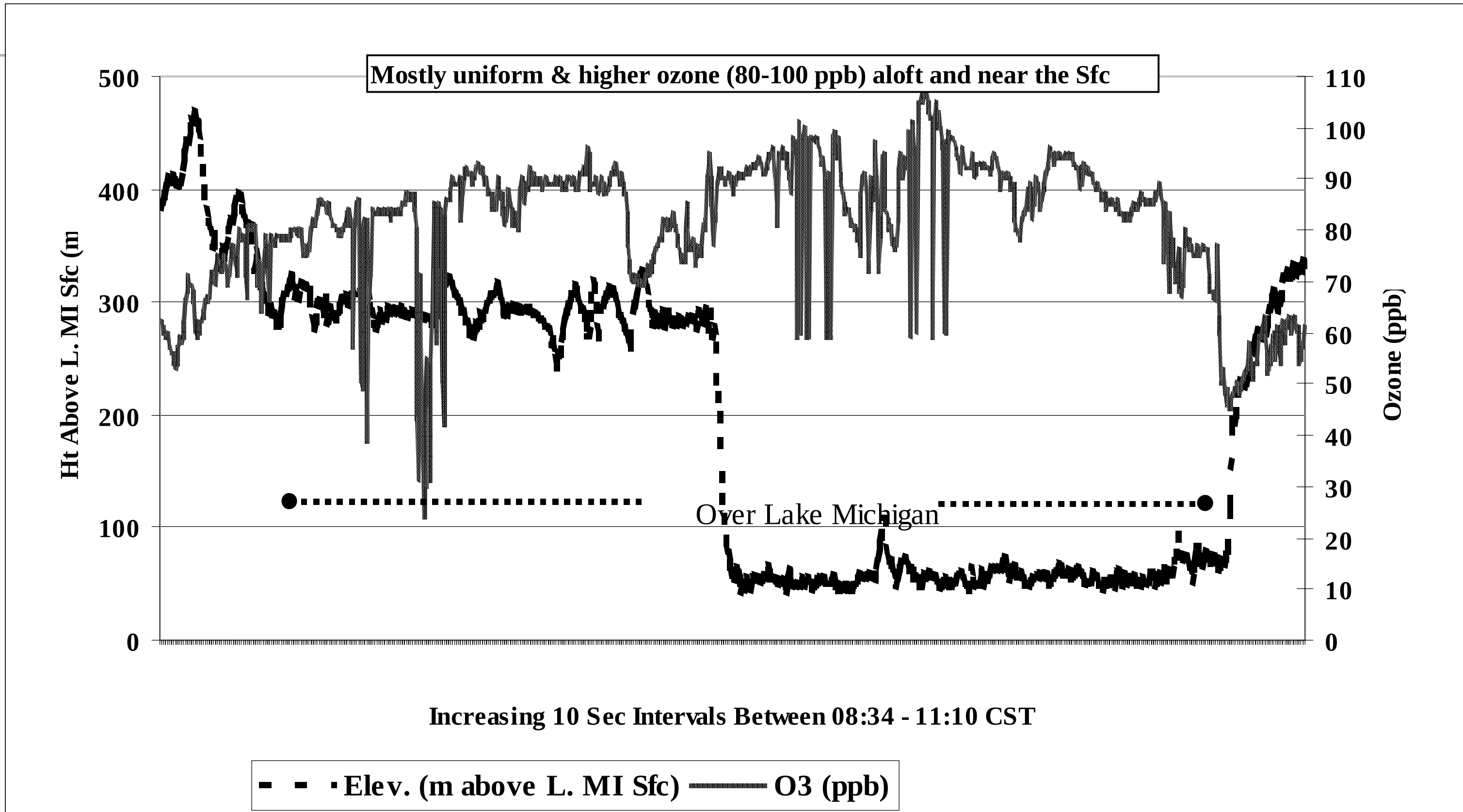
<u>6/22/02 Lake Mich. area surface synoptic meteorology:</u> The front continued to transform -- becoming a warm front, further east-west oriented, and began to slowly move northward between the two surface high pressure systems. The result was that an increasing portion of the southern L. Mich region came under the influence of the high pressure system whose surface center had migrated southwest to the mid-Atlantic states. For the southern half of the L. Mich. area -- these synoptic conditions resulted in weak, predominantly southerly winds drawing up warm (temperatures up to 33 C), humid (dew points temperatures to 25 C) air from the southeast, including high pollution areas such as the Ohio River Valley.

Figure 13: Time Series
Ozone & Height Above L. Mich Level
WDNR Monitoring Flight A
04:35-07:16 CST 22 June 02
(no meteorological data collected)



Relatively high ozone (to 90 ppb) at approximately 300 m above L. Mich in the early daylight of 6/22 could signify that substantial ozone was carried over from the previous day - perhaps because the O3 was insulated from overnight destruction at the surface by staying aloft due to weak mixing over the Lake. There was only a modest overall decline (10-20 ppb) in ozone at the lower heights (50 m) above the Lake, suggesting that much of this ozone was also generated on 6/21.

Figure 14: Time Series
Ozone & Height Above L. Mich. Level
WDNR Monitoring Flight B
08:34 - 11:10 CST   22 June 02

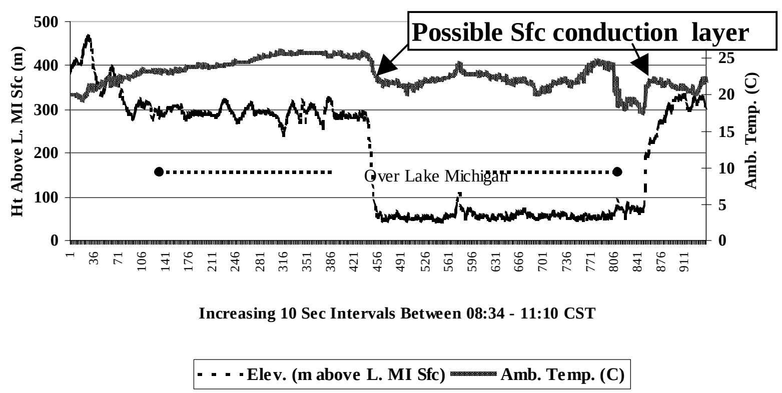


In this mid-to-late morning flight, the ozone levels at about 300 m above L. Mich stayed relatively the same (to 90 ppb) from 3-4 hours earlier. However, there was a considerable ozone increase (about 30 ppb to total levels of 100+ ppb) at the lower heights (50 m) above the Lake. This suggests that both much new ozone and fresh morning precursors reacting into ozone had advected eastward through the Lake's lower atmosphere from the Chicago-Milwaukee region's rush hour activities and other areas further upwind. The considerable drop-off in ozone over land offers speculation that ozone production efficiency might have been optimized in the Lake's shallow conduction inversion layer (see Appendix A), which had stable, cloudless, humid, stagnant air (see Figure 15) -- considered ideal for enhancing photochemical processes.

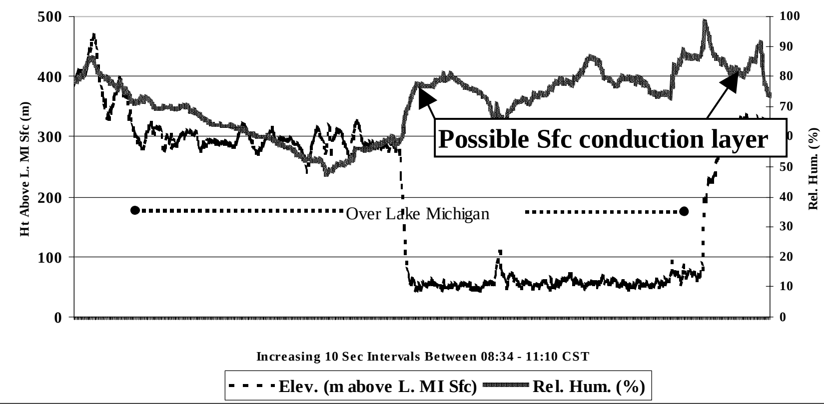
Figure 15: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight B 08:34 - 11:10 CST 22 June 02

At approximately 300 m above L. Mich -- fairly warm (to 25 C) and dry (to 50% rel. hum.). With the plane's descent to 50 m heights came a decrease in temperature and increase in humidity, suggesting that the shallow conduction inversion layer (Appendix A) just above the Lake's surface existed during this flight. Wind speeds were generally weak-to-moderate (3-9 m/s), indicating stagnating conditions, which are favorable to enhancing photochemical production of ozone (App. A). The air flow was largely southwest-to-northwesterly aloft, southerly in the conduction layer. Save for wind speed, the difference in weather characteristics between aloft and the conduction layer suggest a vertical decoupling between these 2 layers.

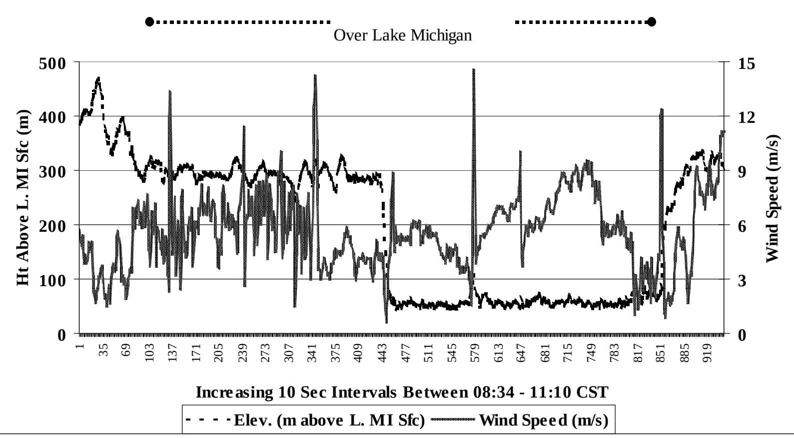
15a) Temperature Aloft



15b) Rel. Humidity Aloft



15c) Wind Speeds Aloft



15d) Wind Dir. Aloft

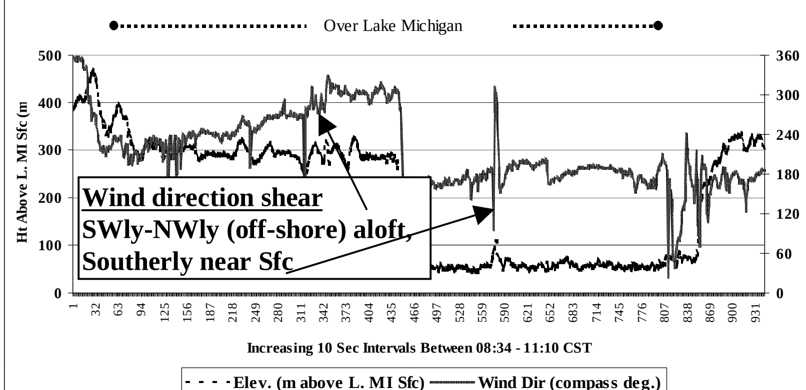
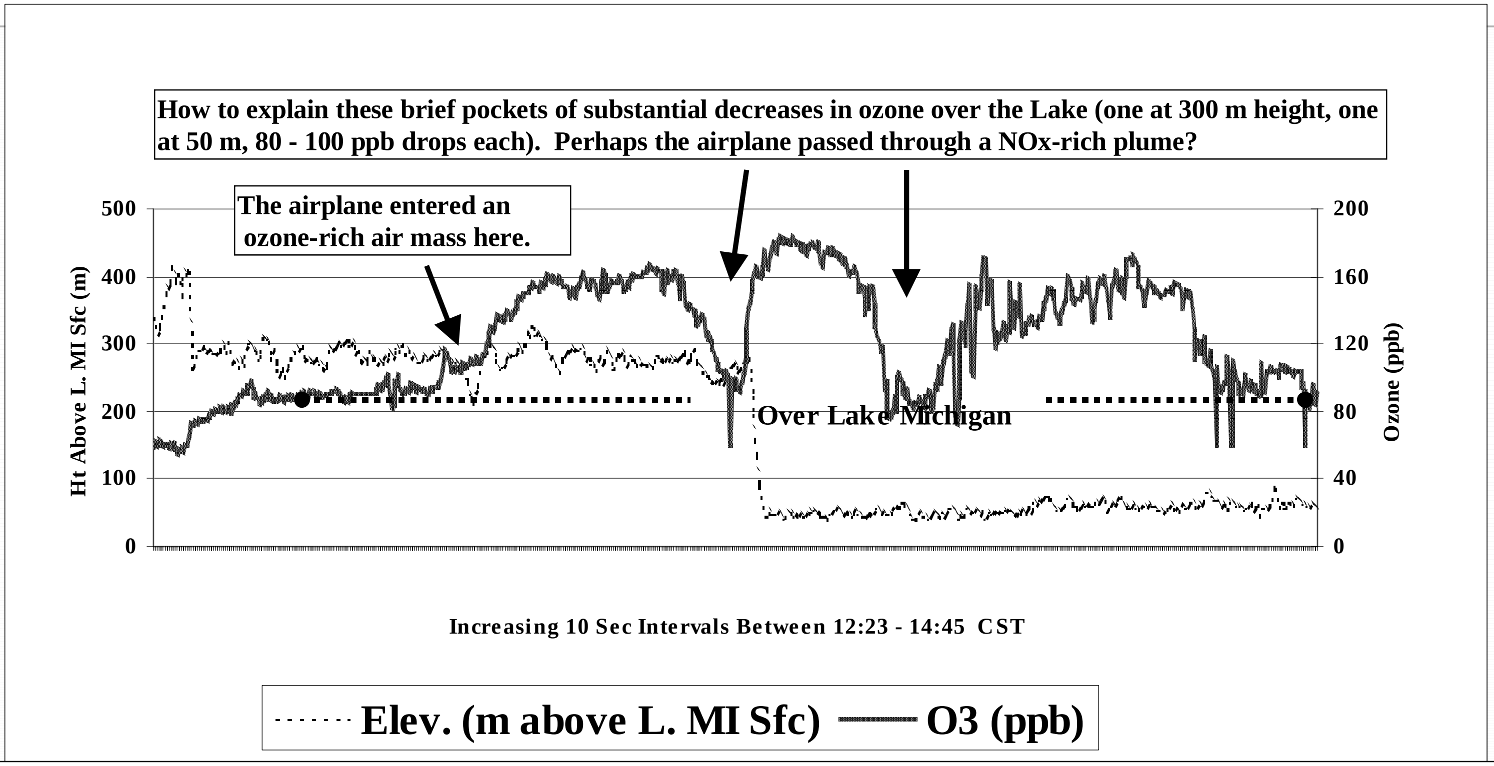


Figure 16: Time Series
Ozone and Height Above L. Mich Level
WDNR Monitoring Flight C
12:34 - 14:46 CST   22 June 02

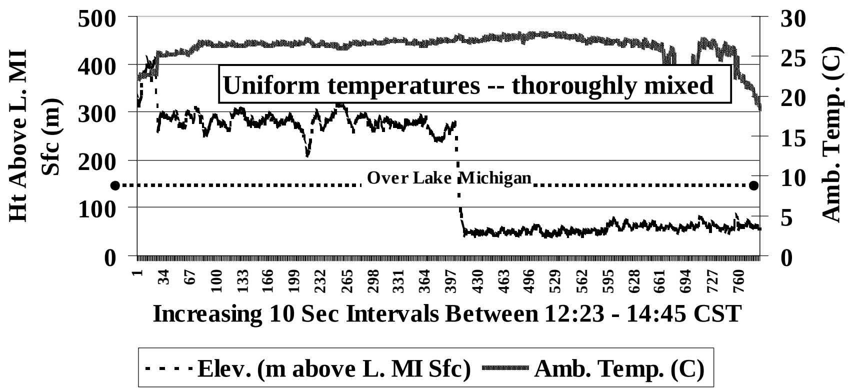


In this early-to-mid-afternoon flight, the ozone levels at about 300 m above L. Mich stayed relatively the same (to 90 ppb) from 3-4 hours earlier until over the southern middle of the Lake, where the plane encountered an air mass with 160 ppb ozone. Estimating how much of this considerable ozone aloft was transported offshore and how much was formed over the Lake would be a worthwhile study. These very high ozone concentrations were largely sustained as the airplane descended to 50 m above the Lake. A couple pockets of greatly diminished ozone are noted in a caption box above the graph. Note that over both land and the near-shore Lake -- relatively low ozone (80-100 ppb) was monitored. This suggests that conditions ideal for producing ozone were much better over the Lake's interior areas, not over the land and near-shore lake on 6/22.

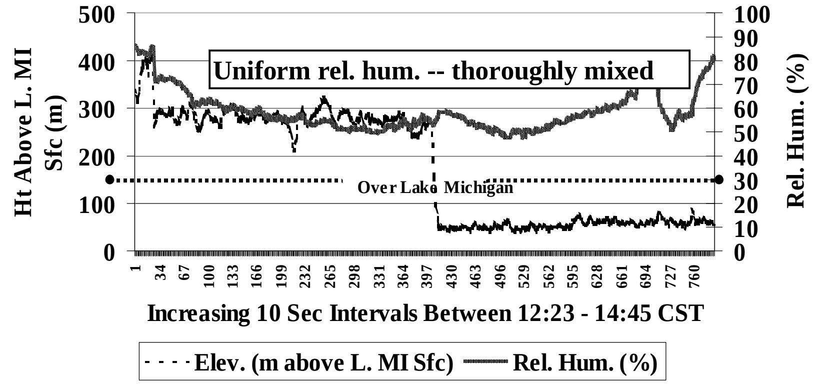
Figure 17: Time Series
Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight C
12:23 - 14:46 CST 22 June 02

These measurements show that the air mass up to 300 m above the Lake's surface was uniformly mixed with warm (27-28 C) & moderately humid (50-70% rel. hum.) air by early-to-mid-afternoon on 6/22 -- indicating the absence of the near-surface conduction inversion during this flight. The modest wind speeds were slightly higher aloft than near the surface. And there was wind directional shear: approximately from 210-230º (offshore or) aloft and from 160-180º (mostly onshore) near the surface. This supports a conceptual model of directional shear in a developed lake breeze (App. A).

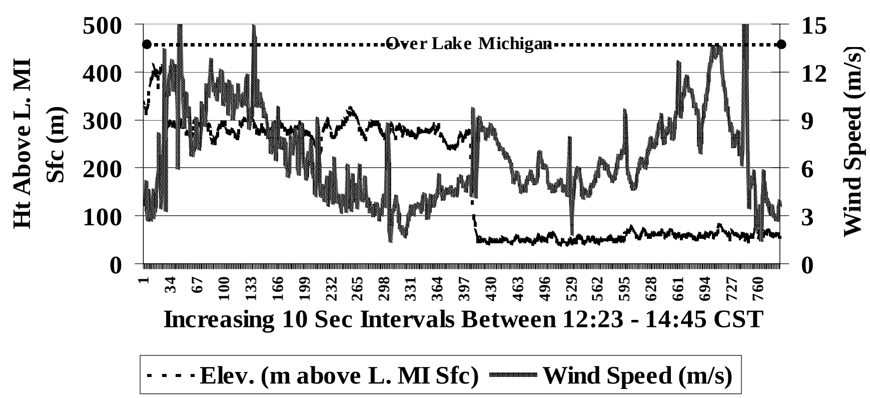
17a) Temperature Aloft



17b) Relative Humidity Aloft



17c) Wind Speed Aloft



17d) Wind Direction Aloft

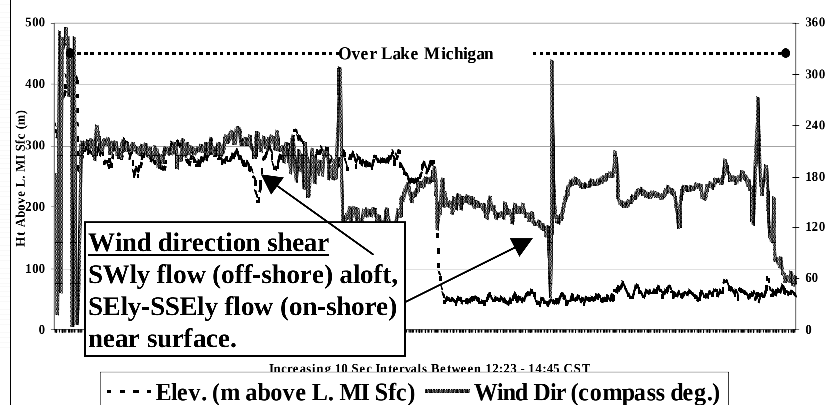
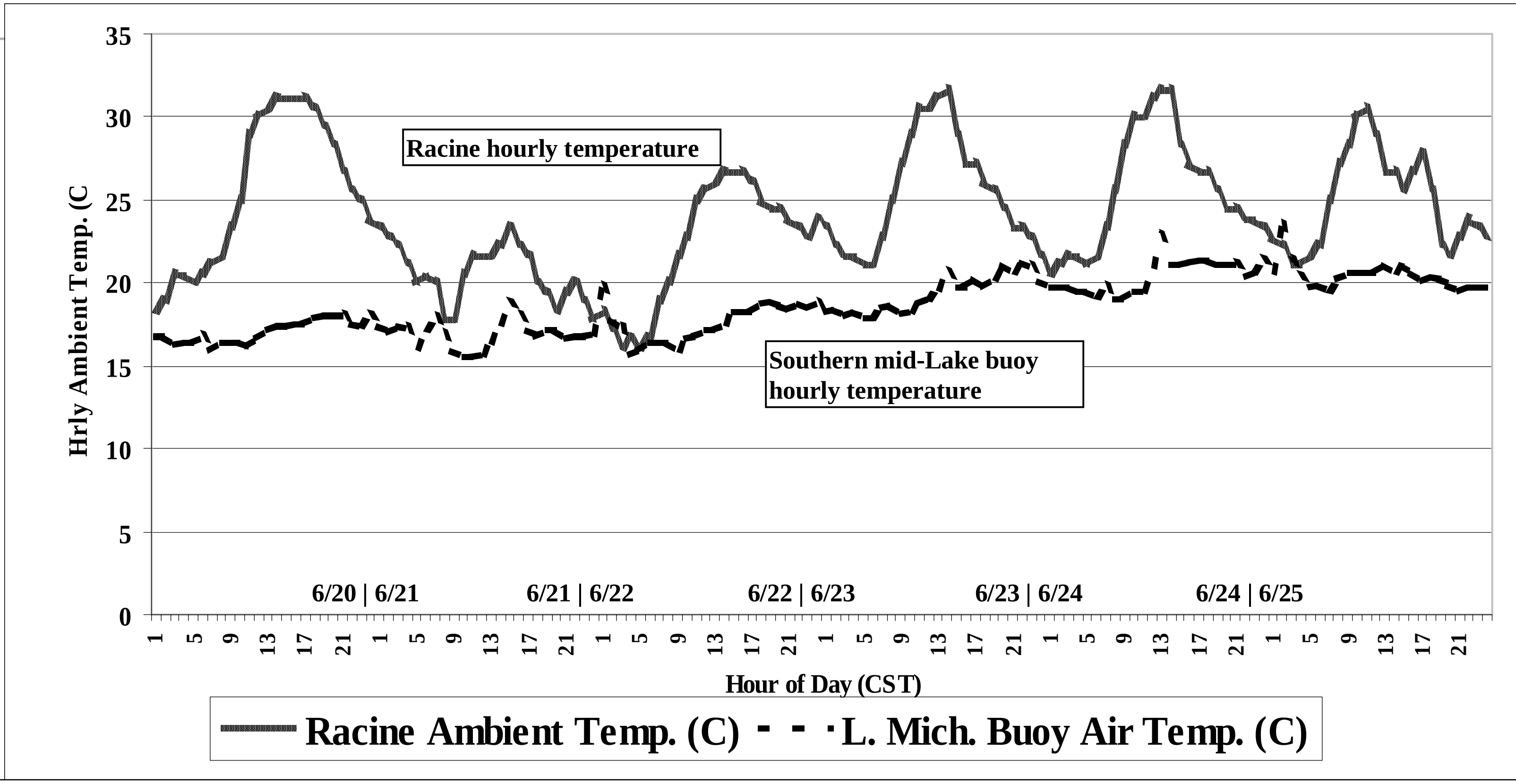
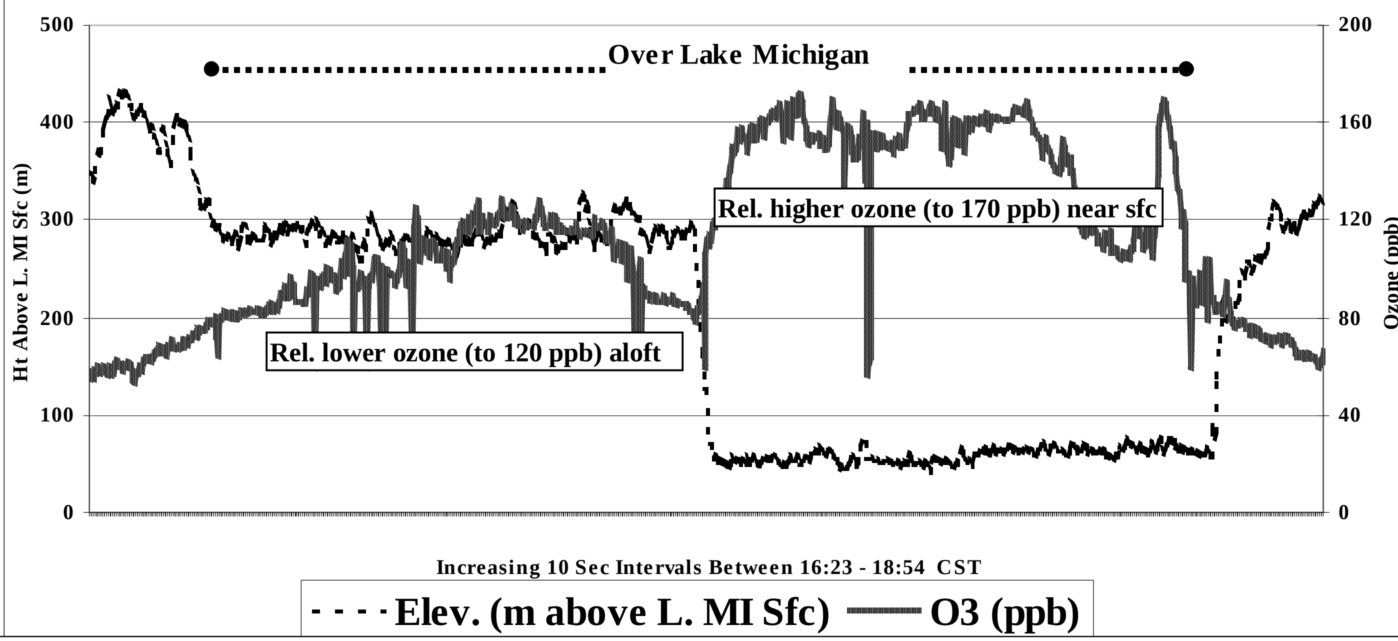


Figure 18: Time Series
Hrly Surface Air Temperature
Racine, WI and S. Lake Mich. Buoy
20 - 25 June 02



This graph shows that during the ozone episode -- daytime temperatures at the Racine monitor were substantially warmer (10-15 C) than at the southern L. Mich. buoy, which is located approximately 45 km east of Racine. This daytime "cold lake-warm land" situation is necessary to help establish a thermodynamically-driven lake breeze circulation cell (see Appendix A). Of further note is the relatively uniform temperatures measured at the buoy. This indicates that a shallow conduction inversion layer was likely present over the Lake (identified in Figure 15a) during much of this episode. The conduction inversion is a stable, cloudless air mass that is considered to be a favorable "reaction chamber" for the photochemical production of ozone from fresh precursors that are advected from land into it (see Appendix A).

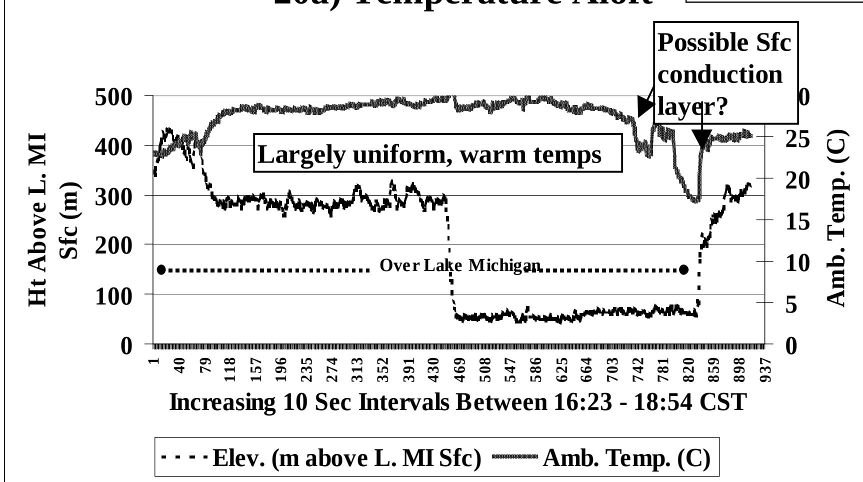
Figure 19: Time Series
Ozone and Height Above L. Mich. Level
WDNR Monitoring Flight D
16:23 - 18:55 CST   22 June 02

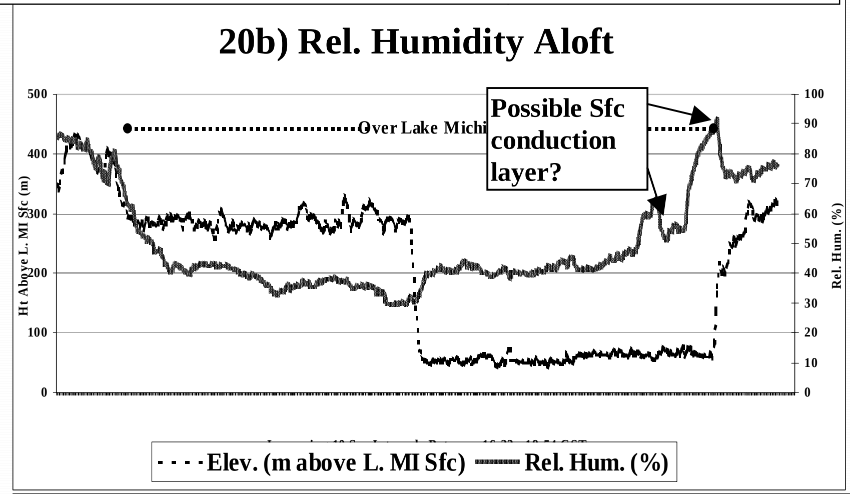


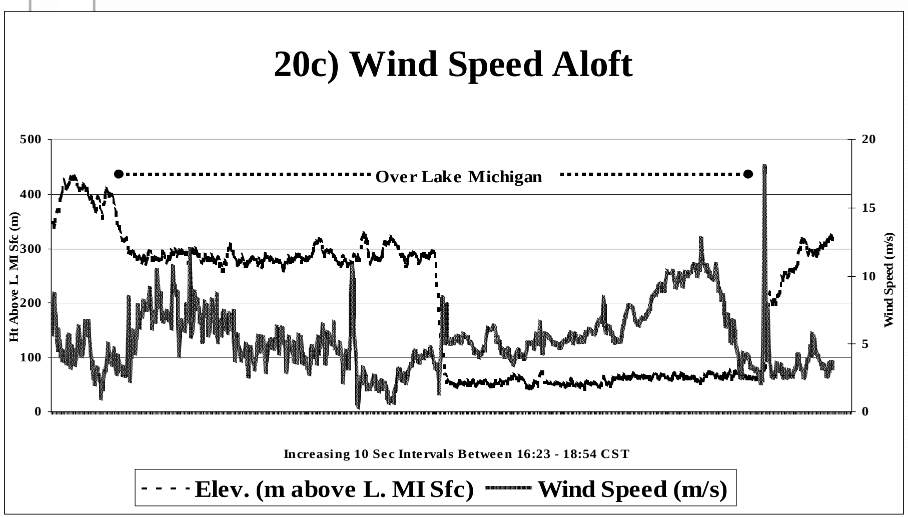
In this late afternoon-early evening flight, the ozone levels at 300 m above L. Mich dropped approx. 40 ppb to approx. 120 ppb from 4 hrs earlier (Flight C, Fig. 16), indicating that ozone production and/or ozone transport into this zone was waning. However, the high ozone concentrations (approx. 160 ppb) at the 50 m hts were sustained from the previous flight. This vertical ozone profile over the Lake is a complete reversal from the measurements 12 hours earlier (Flight A, [Fig. 13[), when ozone was greater at the higher elevations than near the surface. As also noted in Fig. 16 -- ozone levels over land were considerably lower (approx. 60 ppb) -- again indicating that meteorological conditions over the central portion of the Lake were much more favorable to ozone photochemistry than over land & near-shore Lake.

Figure 20: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight D 16:23 - 18:55 CST 22 June 02

These Flight D measurements show that the air mass up to 300 m above the Lake's central surface continued to be uniformly mixed with very warm (29-30 C) & slightly dry (40-50% rel. hum.) air during the late afternoon-to-early evening on 6/22 -- again indicating the absence of a near-surface conduction inversion (Appendix A) during this flight. The shear in the wind direction (noted 1st in Flight C [Fig. 17]) between aloft (off-shore flow) and near-surface (on-shore winds) was enhanced here -- suggesting a still-vibrant lake breeze circulation cell during this period.







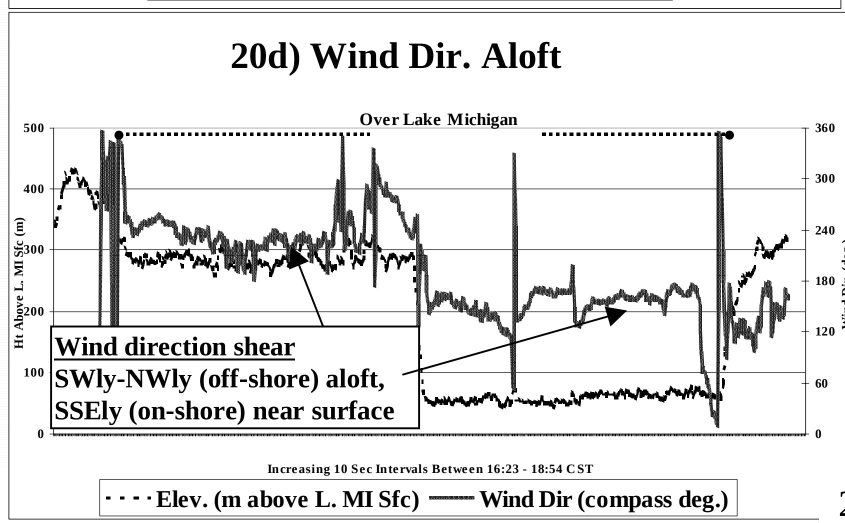
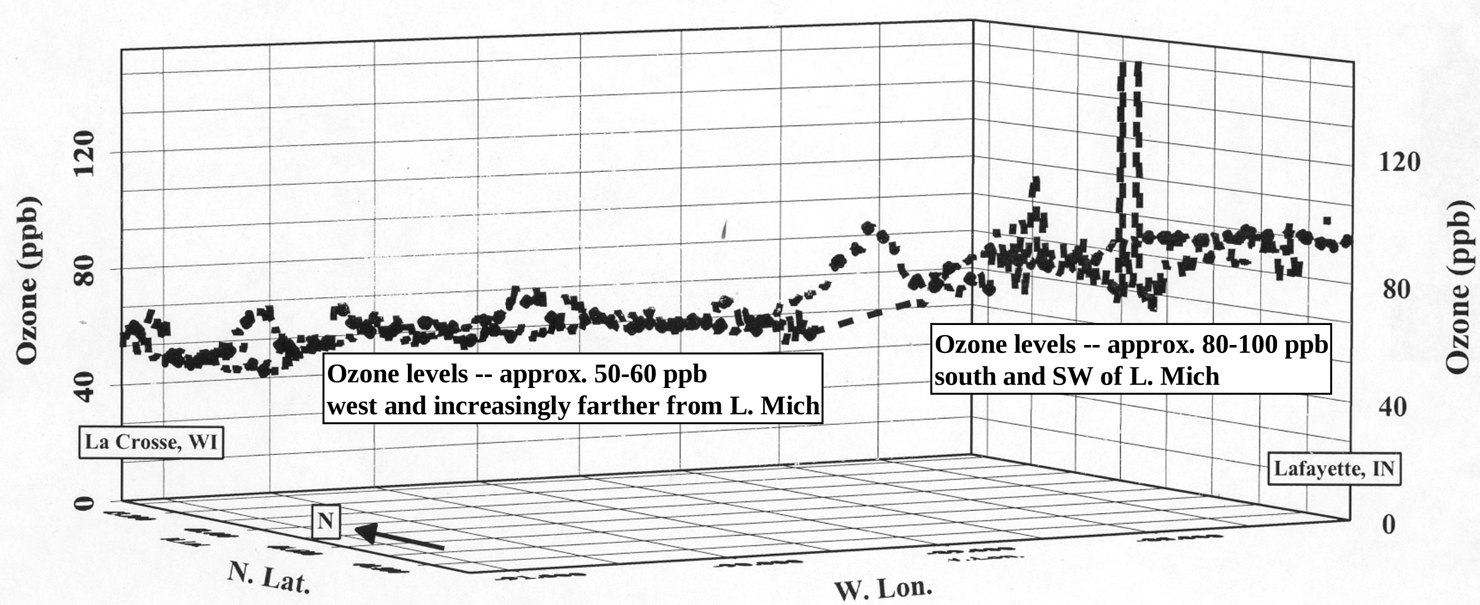


Figure 21: Ozone Aloft
RB Jacko L. Mich. "Boundary" Flight
Saturday, 22 June 02
Westbound: Lafayette, IN - La Crosse, WI 08:41-12:35 CST[a]
Eastbound: La Crosse - Lafayette 12:35-14:48 CST

The ozone profile on the return leg largely retraced that for the outbound portion of this flight that was predominantly upwind of Lake Mich. The ozone was somewhat uniform through the vertical, despite the up-and-down element in the airplane's path trajectory (Fig. 5) -- indicating that the ozone was well-mixed vertically in this region. The ozone was higher (90-100 ppb levels) in the areas south and SW of L. Mich, steadily less so to the west and away from the Lake. This supports the evidence of southerly-to-southwesterly winds feeding into the southern L. Michigan basin on this day (Figs 12, 15, 17 & 20).



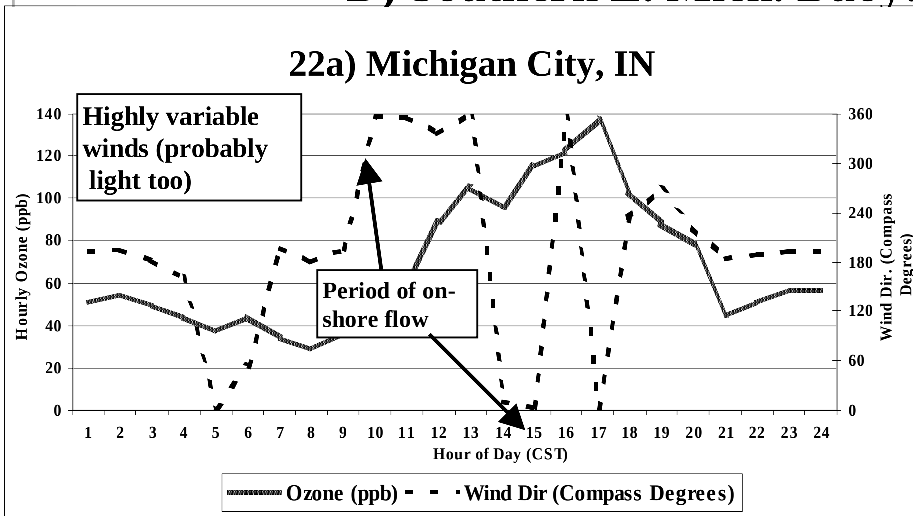
(a) Note: Westbound -- there was a flight layover (no data collected) during 09:23-11:22 CST at the Aurora, IL airport.

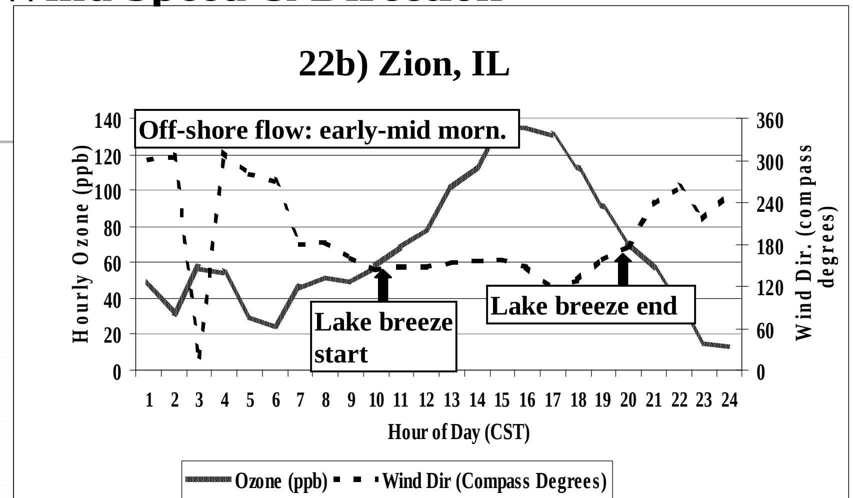
Ozone measurements (10 second averages) were taken at heights varying between 70 and 900 meters above the average elevation of the L. Michigan surface, which is approximately 170 m above mean sea level. According to Prof. Jacko, the original ozone data are perceived to be 1/2 the true value. Consequently, each individual ozone point displayed here is twice what was originally logged.

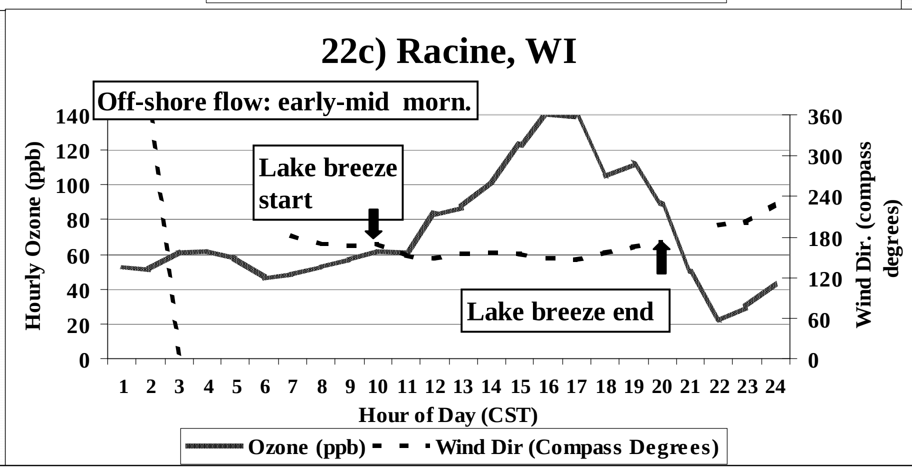
Figure 22: Time Series -Hrly Surface Data - 22 June 02

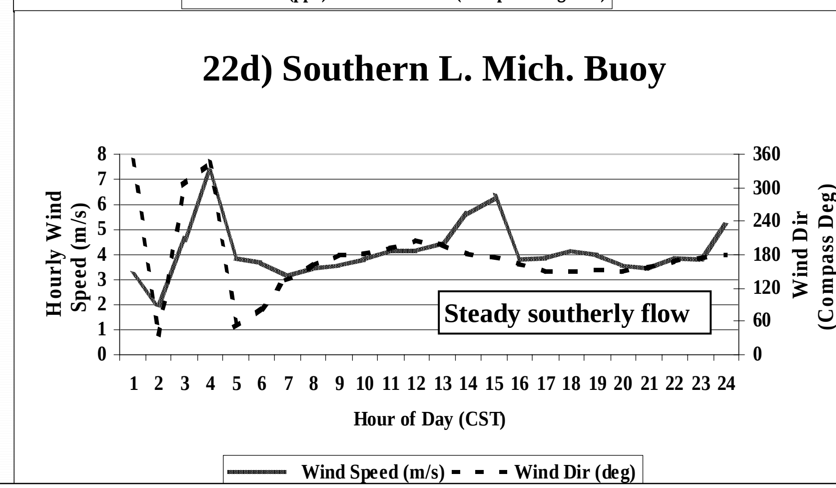
A) Michigan, IN B) Zion, IL & C) Racine, WI: Ozone & Wind Dir.

D) Southern L. Mich. Buoy: Wind Speed & Direction





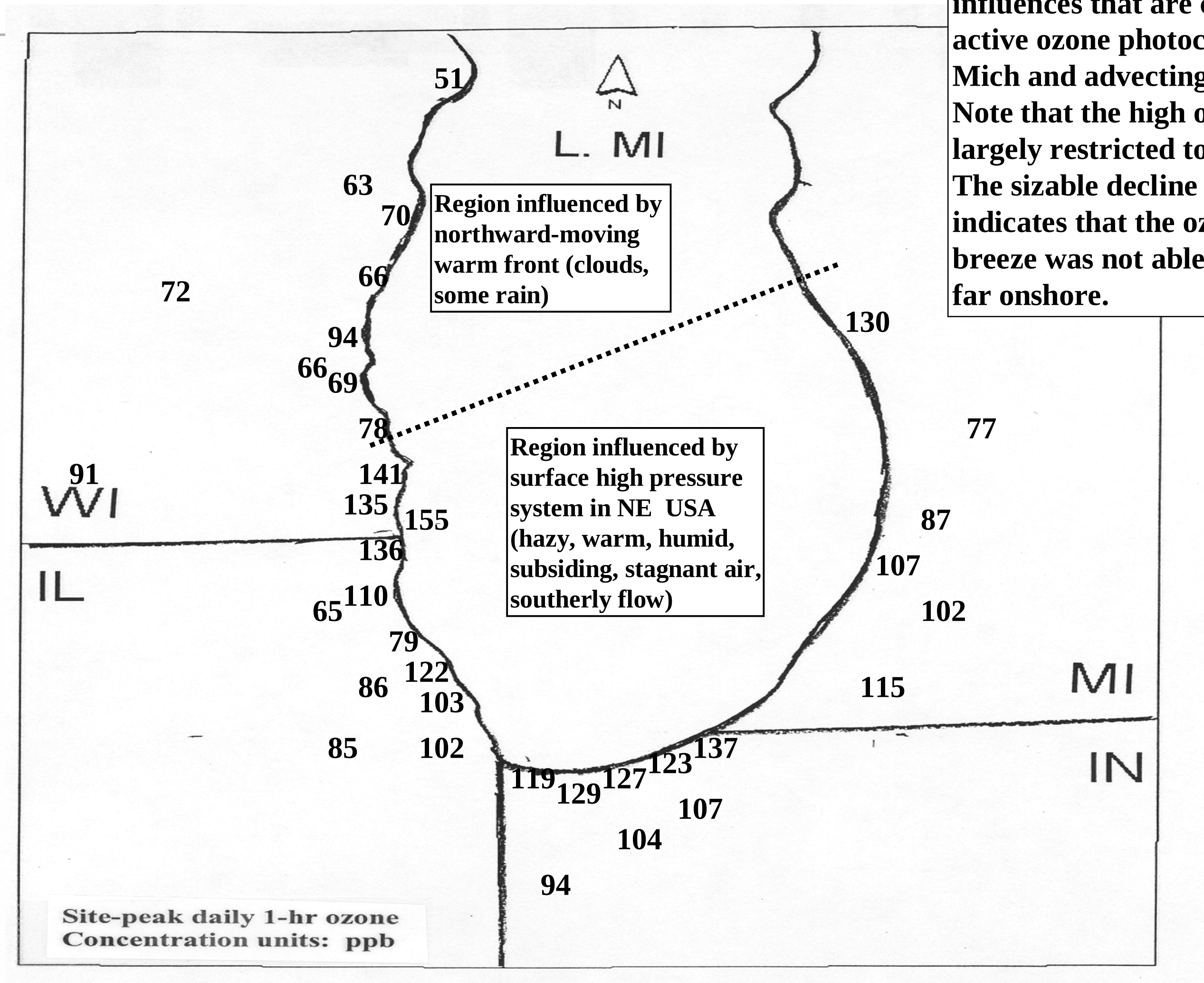




<u>6/22/02 surface</u>: Michigan City saw highly variable (& probably light) winds throughout the day. These stagnant, poorly-mixed conditions contributed to the site's high ozone (140 ppb). Both Zion & Racine had the winds shift from SSWly (slightly off-shore) to SSELy (slightly on-shore flow) by mid-to-late morning. This weak lake breeze (also seen in Fig. 20d) advected ozone on-shore -- such that these sites also witnessed peak ozone near 140 ppb. Conversely, when the lake breeze ended at both sites (reverting back to offshore flow) around 1700 CST -- O3 levels began plummeting to approx. 60 ppb. The Lake buoy saw mostly weak, southerly flow -- indicative of subsidence due to the high pressure's influence -- conditions supportive to developing a lake breeze.

Figure 23

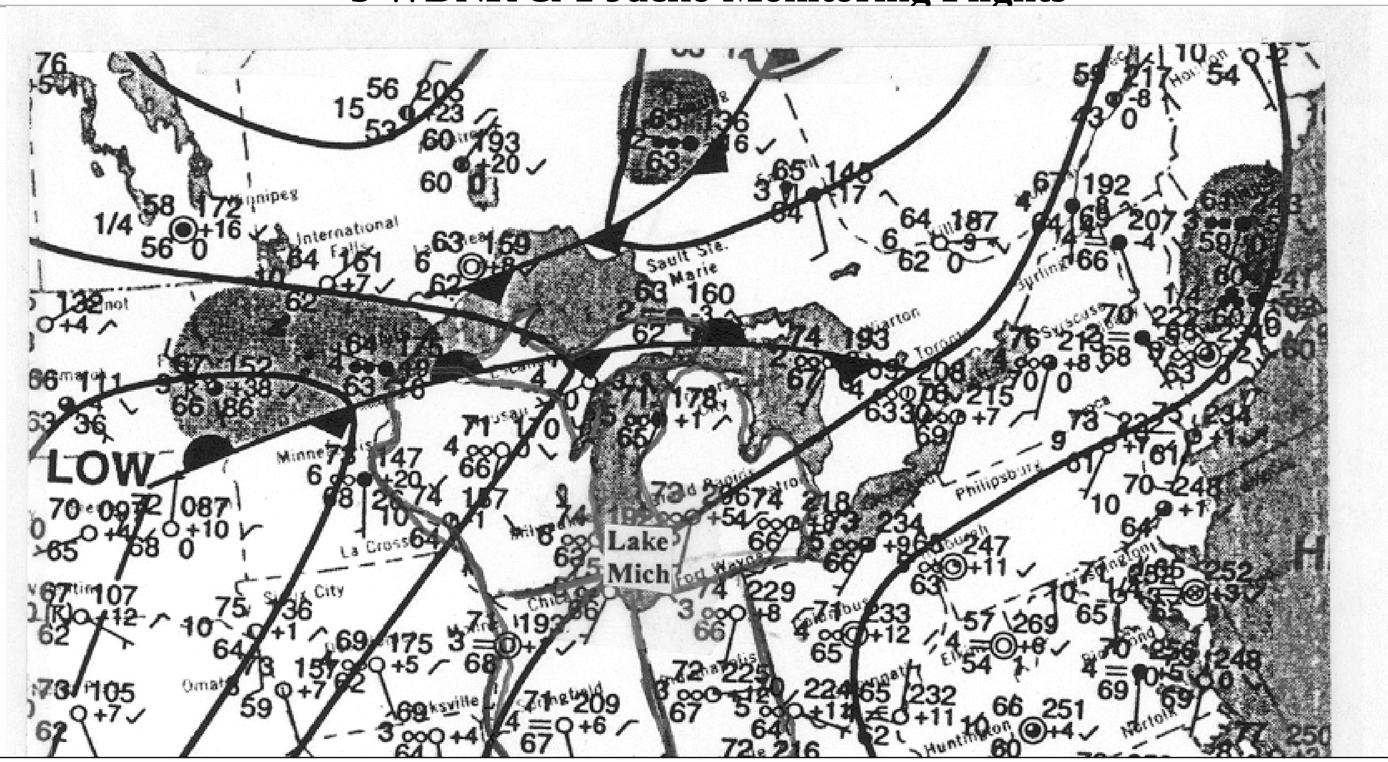
Site Peak-Daily 1-Hr Ozone (ppb)
Monitoring Sites in the S. Lake Mich. Area
22 June 02 (Saturday)



__6/22/02 Peak surface ozone:__ **Similar to 6/21 (Fig. 11), the distibution of ozone levels clearly reflect which area was dominated by the warm front's clouds & rain -- and which region witnessed the high pressure influences that are conducive to the active ozone photochemistry over L. Mich and advecting ozone onshore. Note that the high ozone levels were largely restricted to near-shore sites. The sizable decline in ozone inland indicates that the ozone-laden lake breeze was not able to penetrate very far onshore.**

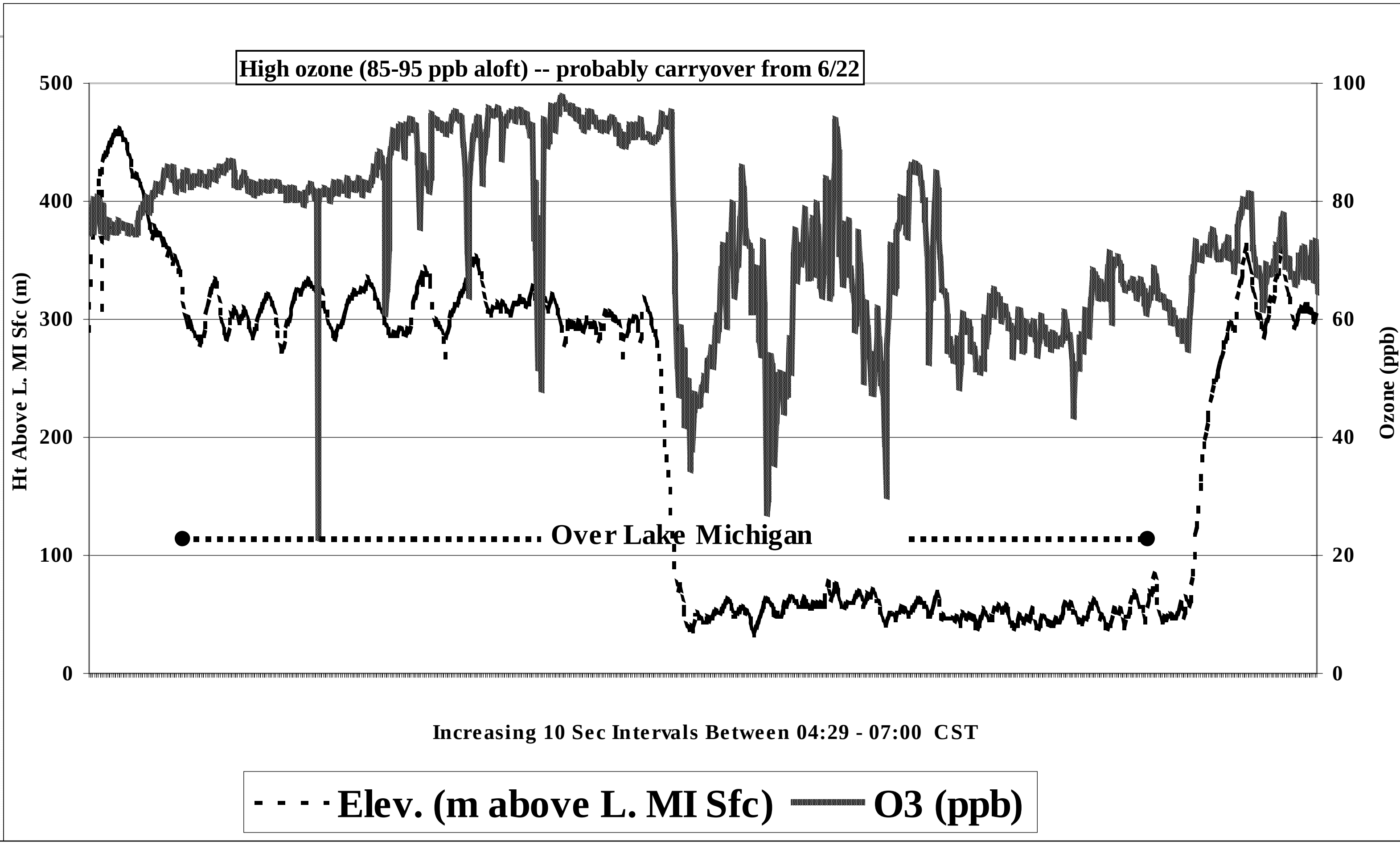
Figure 24

Surface Synoptic Weather Map
6 AM CST 23 June 02
(Sunday -- Episode Day 3)
3 WDNR & 1 Jacko Monitoring Flights



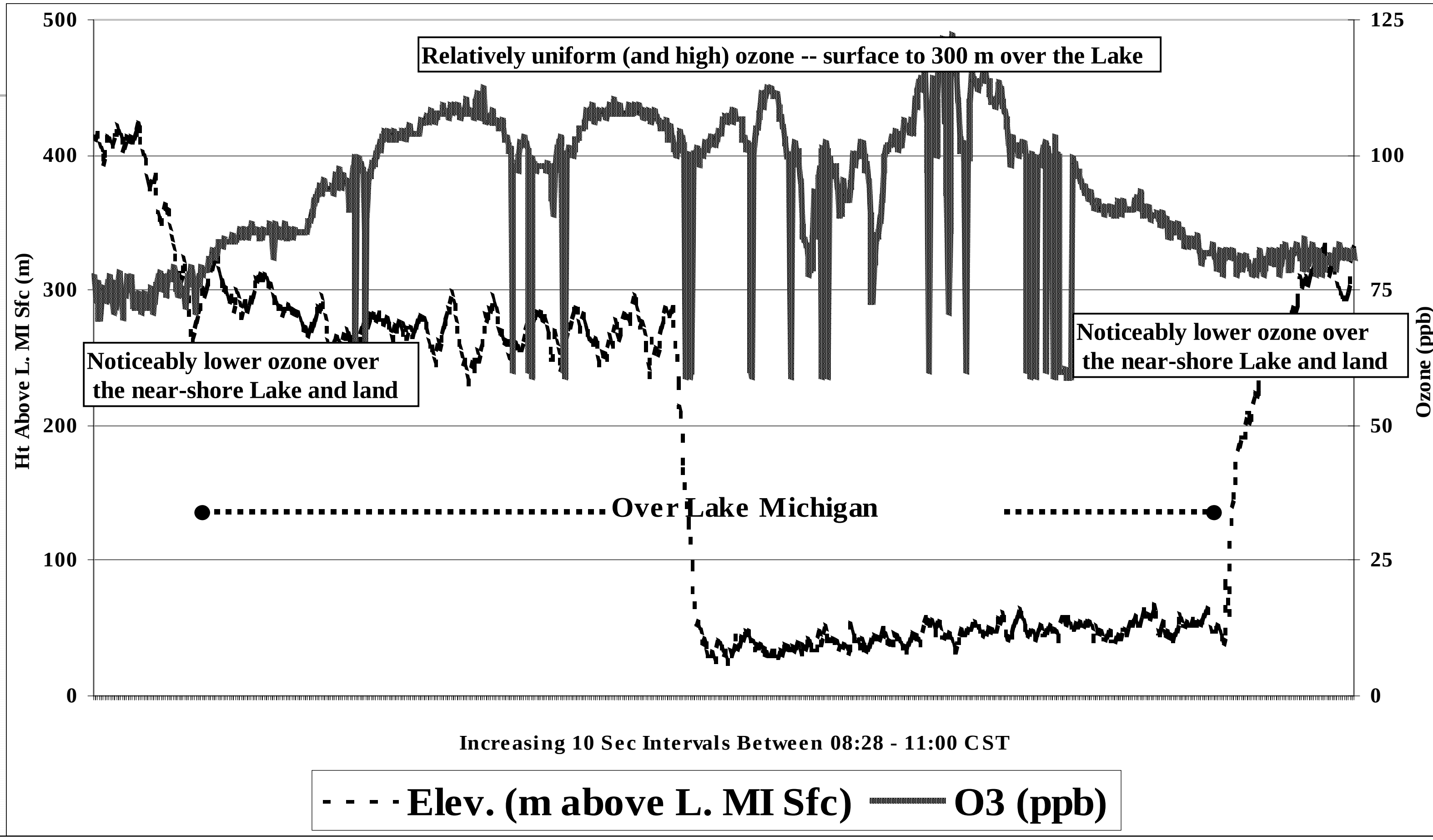
<u>6/23/02 Lake Mich. area surface synoptic meteorology:</u> The front continued to transform -- becoming a stationary front, migrating further northward. The result was that an increasing portion of the L. Mich region came under the influence of the high pressure system, whose center had moved to just off the Delaware coast. South of the front's clouds -- the high pressure's synoptic-scale weak, predominantly southerly winds drawing up warm, humid air from the southeast, including high pollution areas such as the Ohio River Valley. Being the second full day of such weather through out the southern L. Mich area helped assure that a continued buildup of ozone was likely.

Figure 25: Time Series
Ozone and Height Above L. Mich Level
WDNR Monitoring Flight A
04:29 - 07:00 CST 23 June 02
(No meteorological data collected on this flight)



Similar to the dawn flight A on 6/22 (Fig. 13) -- the relatively high ozone (to 95 ppb) at approx. 300 m above L. Mich in 6/23's early daylight indicates consider ozone was carried over from 6/22. At the lower heights above the Lake -- a lot of variations in ozone (30 - 80+ ppb). This suggests that there were some areas closer to the Lake's surface where the O3 was insulated from overnight destruction at the surface, and some areas were ozone might have been reduced by processes such as mixing to the surface and /or titrated by early-morning NOx-rich plumes from major NOx sources near L. Michigan.

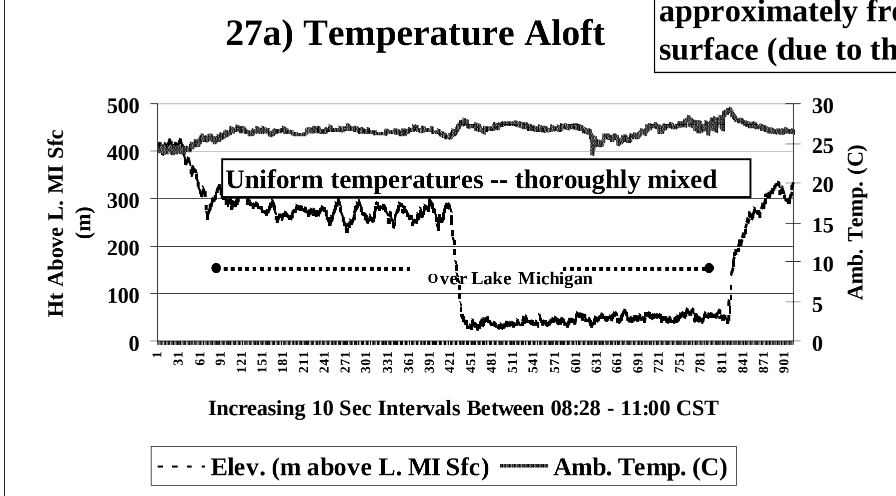
Figure 26: Time Series
Ozone & Height Above L. Mich Level
WDNR Monitoring Flight B
08:28 - 11:00 CST 23 June 02

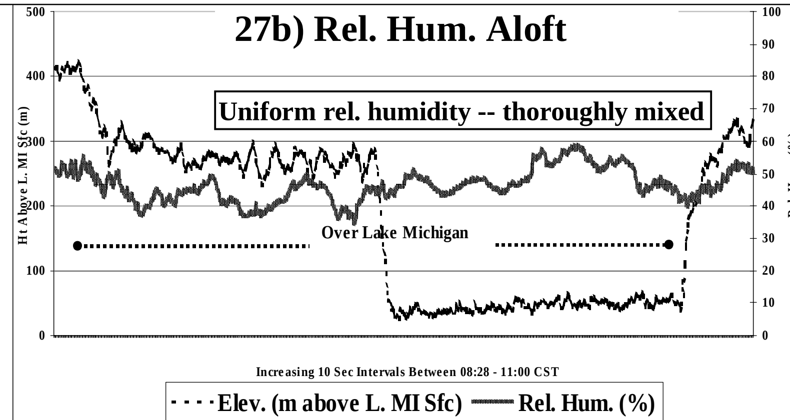


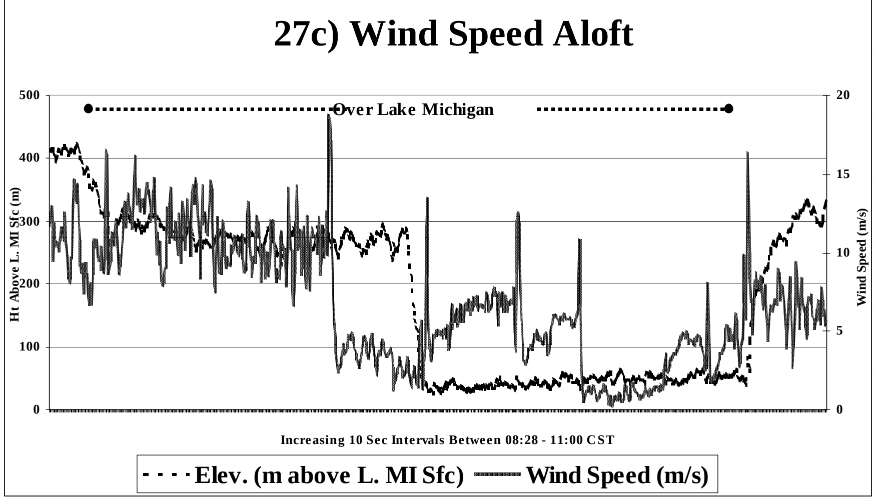
This mid-to-late morning Flight B on 6/23 measured ozone profiles that were similar to Flight B on 6/22 (Fig. 14): The ozone levels at about 300 m above L. Mich increased modestly (about 20 ppb to 110 ppb) relative to 3-4 hours earlier (Flight A, Fig. 25). However, at the lower heights (50 m) above the Lake there was a considerable ozone jump (40-70 ppb) to values peaking at 120 ppb. This suggests that both much new ozone and fresh morning precursors reacting into ozone had advected eastward through the Lake's lower atmospheric levels from the Chicago-Milwaukee region's rush hour activities and other areas further upwind. As in the 6/22 B flight -- there was a sizable reduction in ozone over land and the near-shore. This indicates that ozone production efficiency might have again been optimized in the Lake's shallow conduction inversion layer (see Appendix A).

Figure 27: Time Series
Meteorological Measurements & Height Above L. Mich.
WDNR Monitoring Flight B
08:28 - 11:00 CST 23 June 02

The meteorological profiles measured during this mid-to-late morning Flight B actually bears more resemblance to those captured during the early afternoon Flight C on 6/22 (Figure 17): The air mass up to 300 m above the Lake's surface was uniformly mixed with warm (27-28 C) & moderately humid (40-50% rel. hum.) air by early-to-mid-afternoon -- again indicating the absence of a near-surface conduction inversion during this flight. The average aloft wind speeds (9-12 m/s) were considerably higher than near the surface, which often witnessed near-calm conditions. There was also wind directional shear in the vertical: approximately from 240-270º (offshore flow) aloft and somewhat variable near the surface (due to the weak wind speeds), with occasional pockets of on-shore flow.







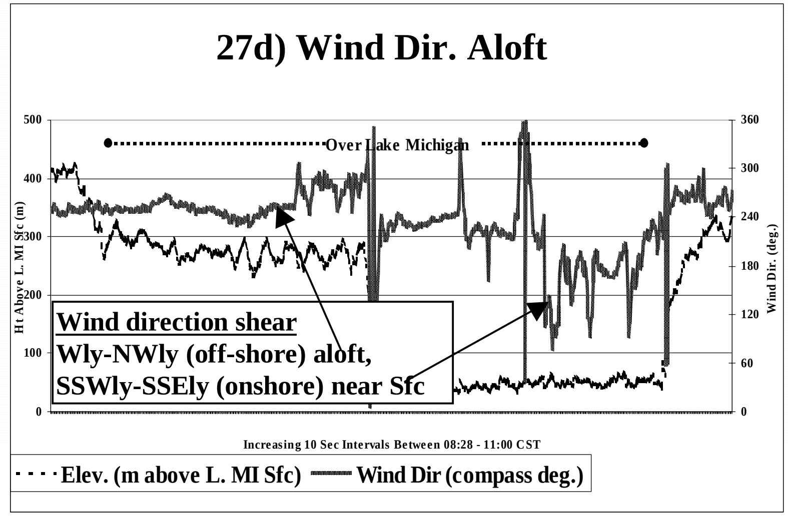
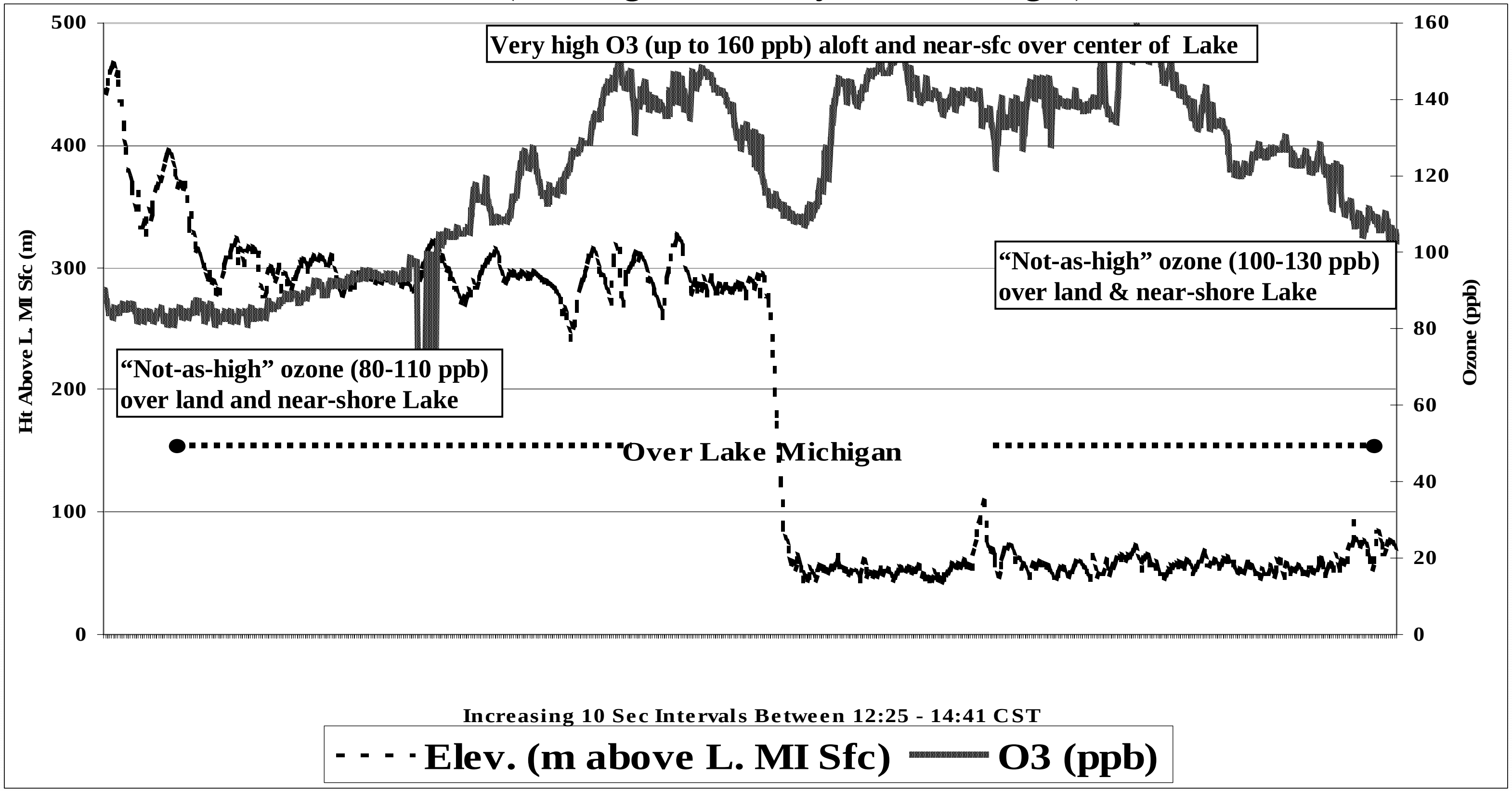


Figure 28: Time Series
Ozone & Height Above L. Mich. Level
WDNR Monitoring Flight C
12:25 - 14:41 CST   23 June 02
(Last flight of the day -- no "D" flight)



This early-to-mid-afternoon flight measured ozone levels that were similar to those from Flight C on 6/22 (Fig. 16): The ozone at about 300 m above L. Mich stayed relatively the same (to 90 ppb) from 3-4 hours earlier (Flight B, Fig. 28) until over the southern middle of the Lake, where the plane encountered an air mass with 150 ppb+ ozone. As on 6/22 these very high ozone concentrations were largely sustained as the airplane descended to 50 m above the Lake (suggesting increased photchemistry through a deeper vertical zone), save for a pocket of greatly diminished ozone during the descent and over the near-shore Lake. As in Fig. 16 - the declining ozone over both land and the near-shore Lake suggest that conditions ideal for producing ozone were much better over the Lake's interior areas on land.

Figure 29: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight C 12:25 - 14:41 CST 23 June 02

The meteorological profiles monitored over the Lake during this afternoon flight on 6/23 strongly resemble those collected during Flight B on 6/22 (08:34-11:10 -- Fig. 15): At approx. 300 m above L. Mich there was fairly warm (to 25 C) and dry (to 50% rel. hum.) air. With the plane's descent to 50 m heights came a decrease in temp. & increase in humidity, suggesting the reappearance of a shallow conduction inversion layer just above the Lake's surface (as seen in the 6/22 Flight B). This inversion was not evident during the 6/23 Flight B (4 hrs earlier [Fig. 27]). Wind speeds were generally weak-to-moderate (3-9 m/s), indicating potentially stagnating conditions -- favorable to enhancing ozone production (App. A). The winds were largely SWly-to-NWly (off-shore) aloft, S to SEly (on-shore) in the conduction layer. Save for wind speed, the difference in meteorology between aloft and the conduction layer suggest a vertical decoupling in the meteorology between these 2 layers -- as in 6/22's Flight B.

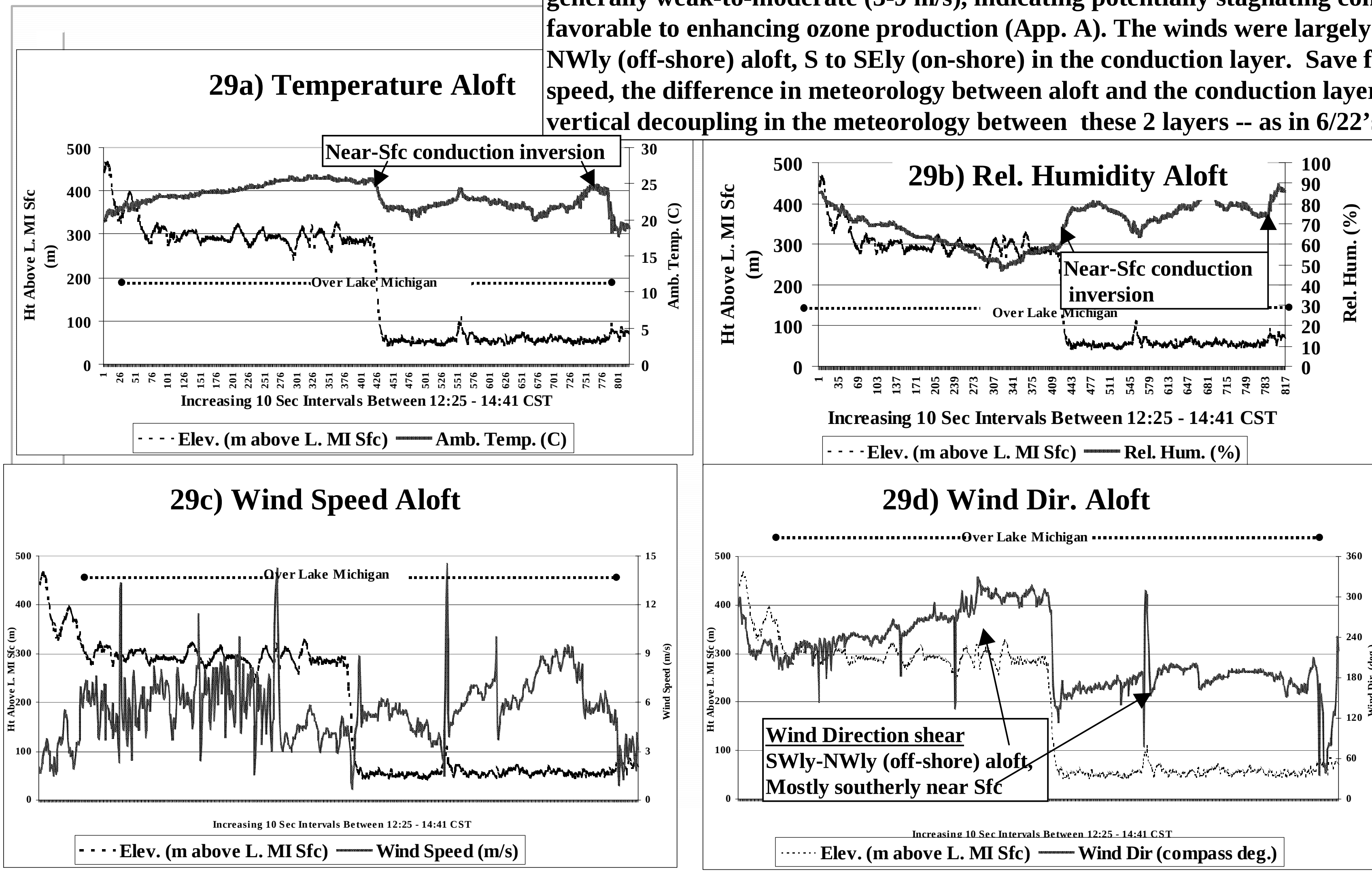


Figure 30: Ozone Aloft

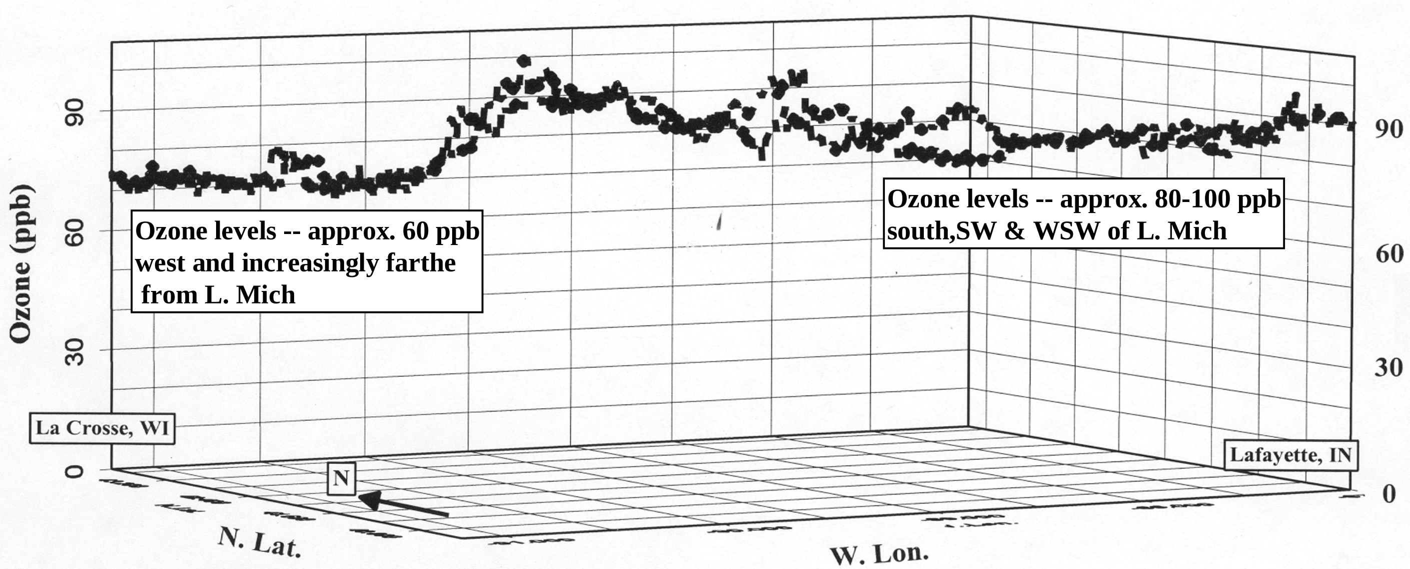
RB Jacko L. Mich. “Boundary” Flight

Sunday, 23 June 02

Westbound: Lafayette, IN - La Crosse, WI 11:03 - 13:18 CST

Eastbound: La Crosse - Lafayette 13:18 - 15:55 CST

As with the RB Jacko boundary flight on 6/22 (Fig. 21) -- the ozone was mostly uniform through the vertical, despite the up-and-down element in the airplane’s path trajectory (see Fig. 5) during the “out” and “return” legs of the flight. This again indicated that the ozone was well-mixed vertically in this over-land region upwind of L. Mich.. Relative to 6/22, this area of high aloft ozone (90-100 ppb) expanded farther west of the Lake. This is a sizable increase in the geographical region of high ozone aloft considered background and incoming to L. Mich. This indicates that the influence of the region’s synoptic-scale meteorological conditions (i..e, due to the high pressure system in the Eastern U.S [Fig.24]) is spreading on the 3rd full day of this episode.

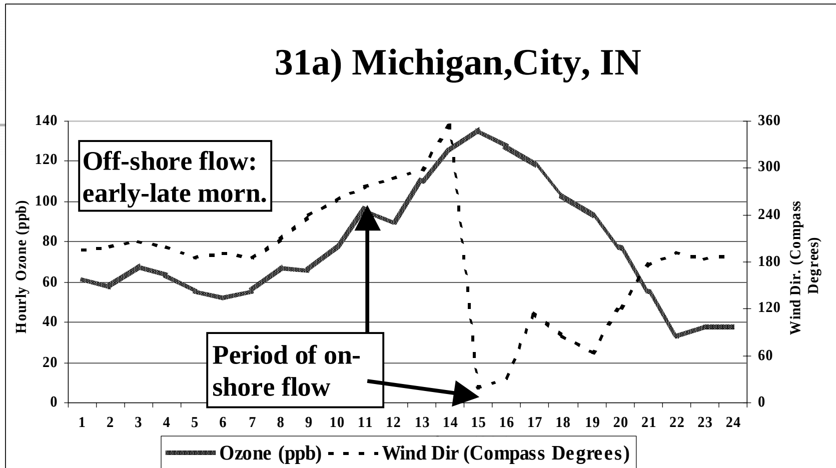


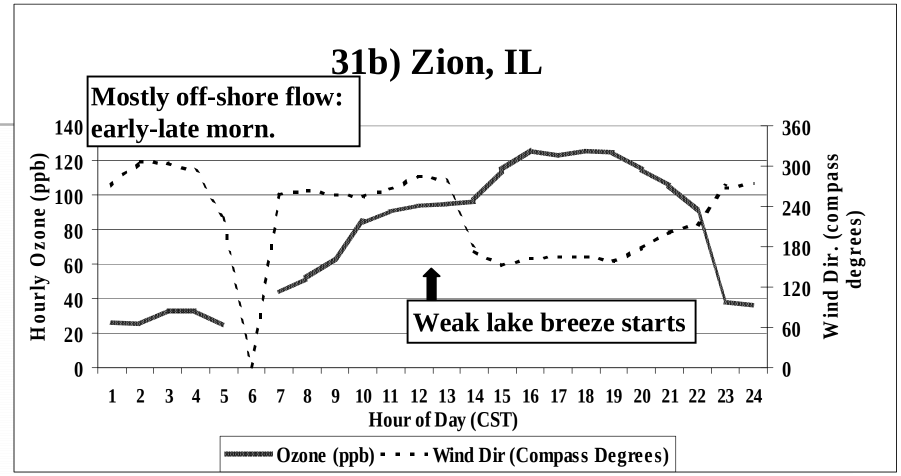
Ozone measurements (10 second averages) were taken at heights varying between 70 and 900 meters above the average elevation of the L. Michigan surface, which is approximately 170 m above mean sea level. According to Prof. Jacko, the original ozone data are perceived to be 1/2 the true value. Consequently, each individual ozone point displayed here is twice what was originally logged.

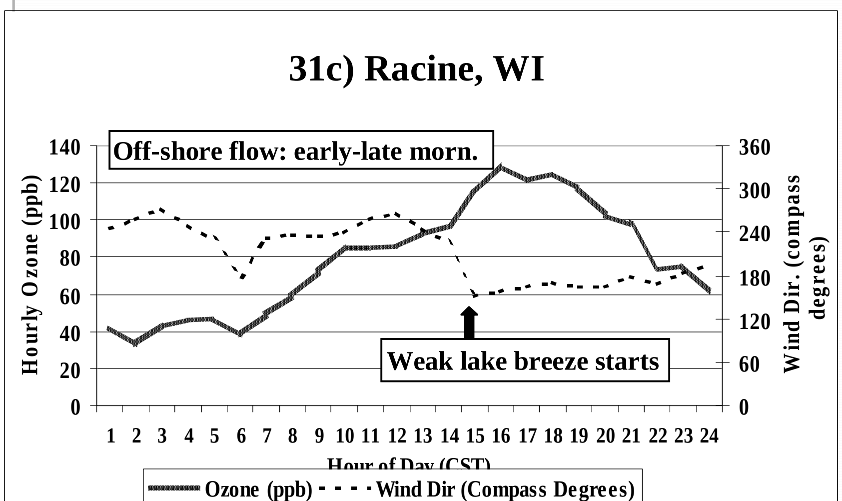
Figure 31: Time Series - Hrly Surface Data - 23 June 02

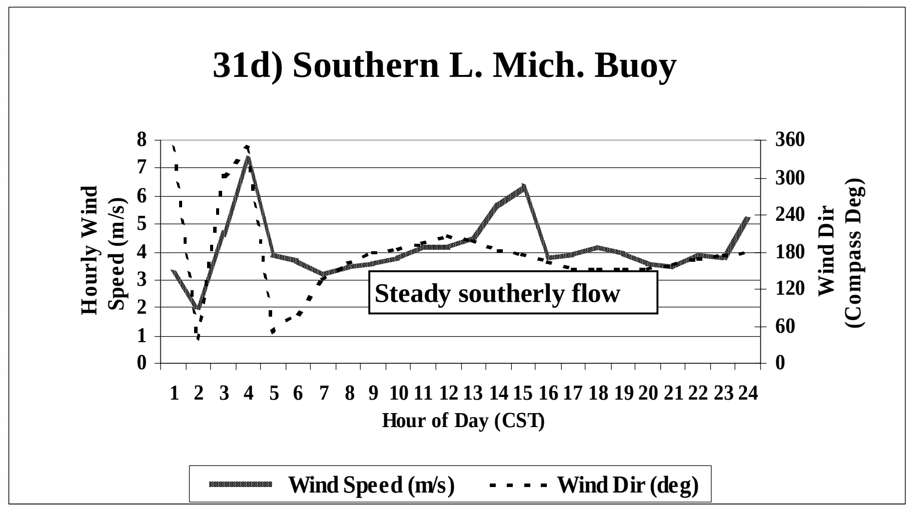
A) Michigan City, IN B) Zion, IL & C) Racine, WI: Ozone & Wind Dir.

D) Southern L. Mich. Buoy: Wind Speed & Direction









<u>6/23/02 surface</u>: **Mich. City had much higher pre-dawn ozone (60 ppb) than either Zion or Racine (30-40 ppb). The wind data does not appear to offer any suggestions as to why. Michigan City witnessed largely northerly (on-shore) winds during about 1000-1600. Both Zion & Racine had lake breezes too -- but later starting (early afternoon) and weaker (less easterly, more southerly) than on 6/22. Nevertheless, all 3 sites monitored ozone that peaked at very high levels (near 140 ppb) on this day. The Lake buoy saw mostly modest (4 m/s) southerly flow (similar to 6/22). This again is evidence of being dominated by a high pressure system.**

Figure 32

Site Peak-Daily 1-Hr Ozone (ppb) Monitoring Sites in the S. Lake Mich. Area

23 June 02 (Sunday)

<u>6/23/02 Peak surface ozone:</u> In general, the high ozone along the shoreline reflects that behind (south of) the northward-moving front (off this map -- in the northern part of the L. Mich region) is the considerable influence from a surface high pressure system situated in the Eastern USA (Fig. 24). Note that the high ozone levels were again largely restricted to near-shore sites (like on 6/22 [Fig 23]) . The sizable decline in ozone inland indicates that the ozone-laden lake breeze was probably not able to penetrate very far onshore.

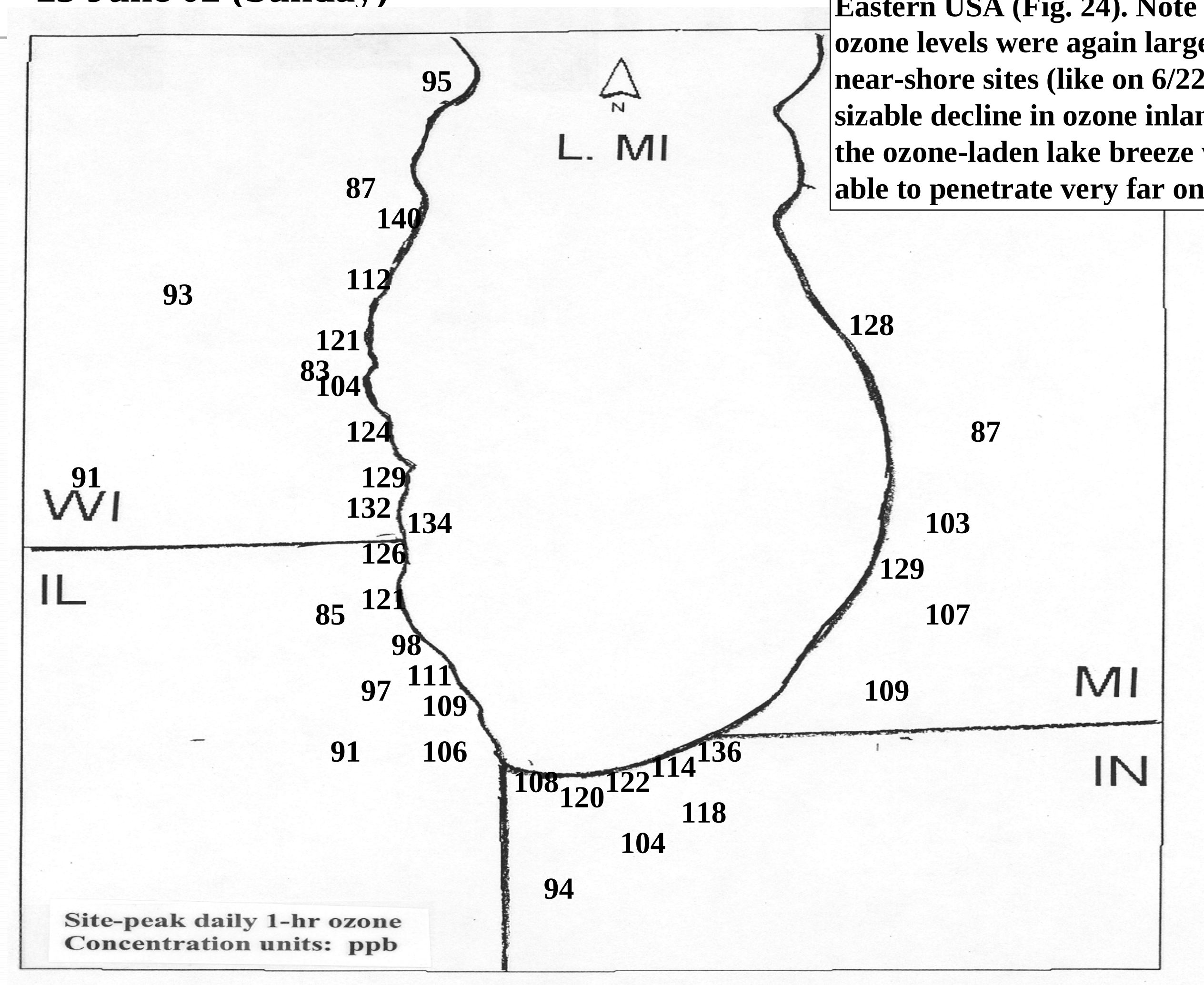
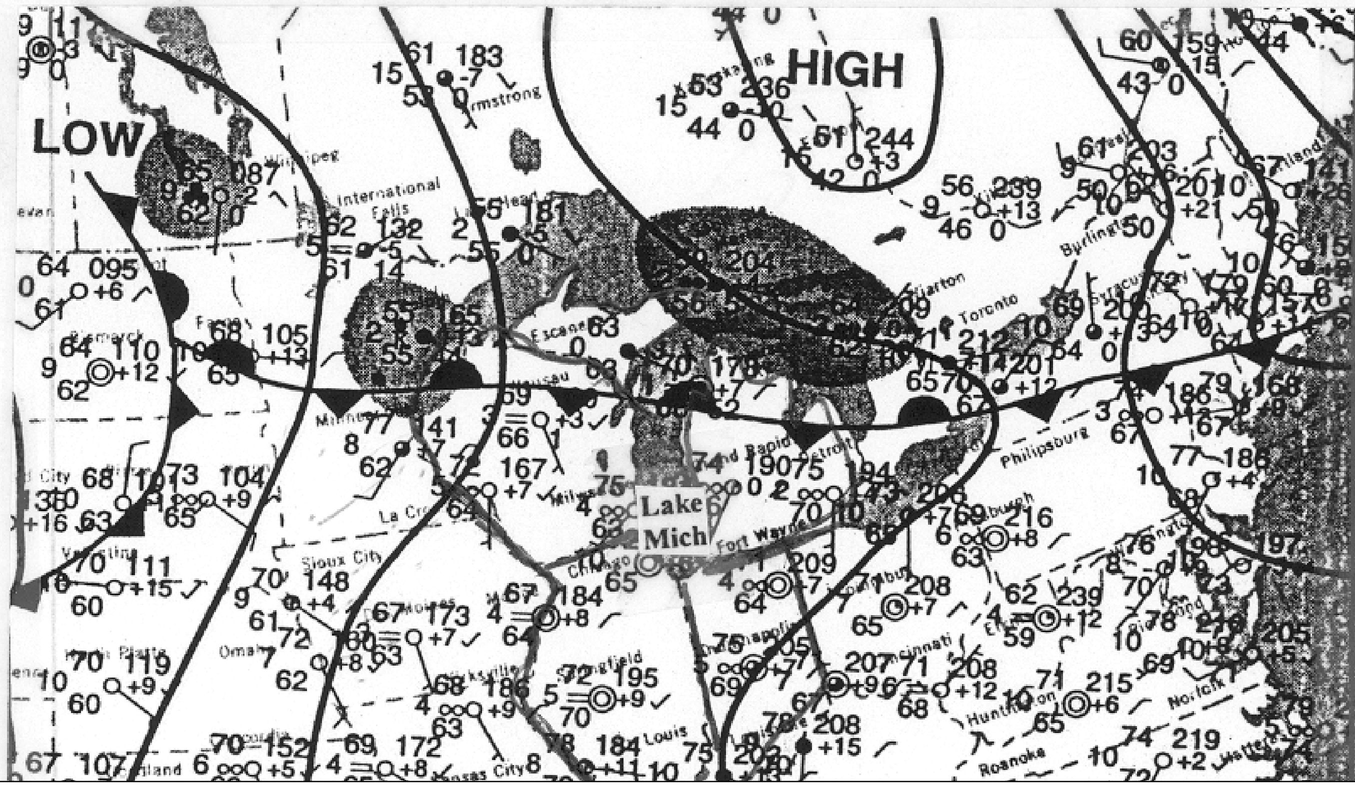
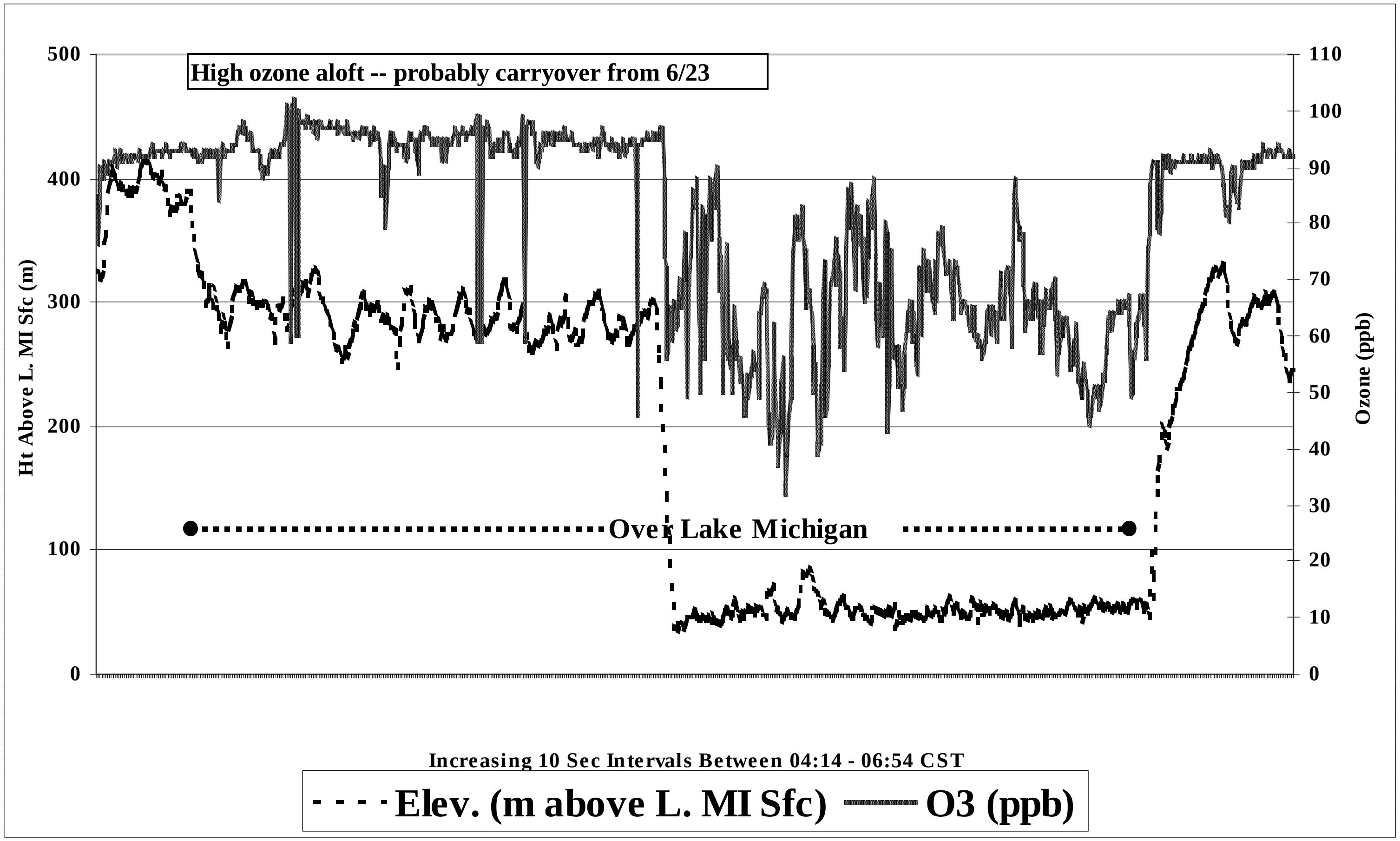


Figure 33
Surface Synoptic Weather Map
6 AM CST 24 June 02
(Monday -- Episode Day 4)
3 WDNR & 1 RB Jacko Monitoring Flights



<u>6/24/02 Lake Mich. area surface synoptic meteorology:</u> **The stationary front moved slightly southward from the day before. The East coast high pressure system, with its ozone conducive weather (i.e., peak temperatures approx. 32-34 C, dew points to 18 C, winds speeds of 3-5 m/s) still dominating the L. Michigan region. However, this system had begun to weaken (in part due to an advancing cold front). There was another cold front moving eastward into Minnesota & Iowa -- not yet impacting the L. Michigan region.**

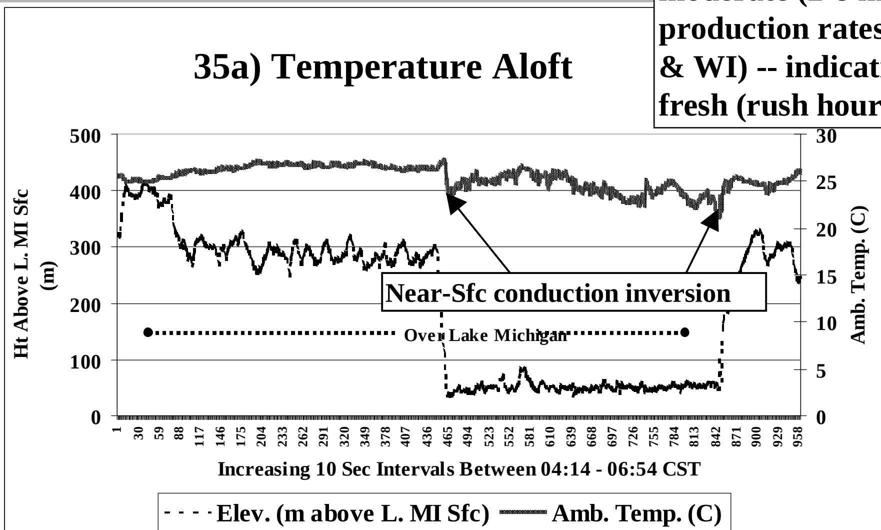
Figure 34: Time Series
Ozone & Height Above L. Mich Level
WDNR Monitoring Flight A
04:14 - 06:54 CST   24 June 02

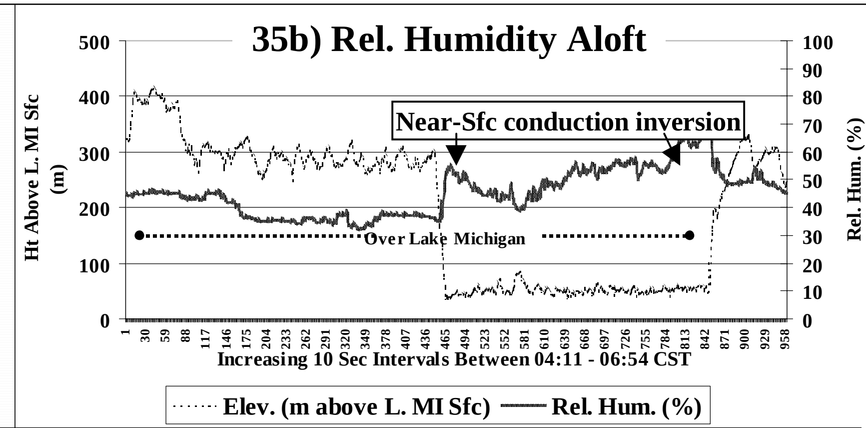


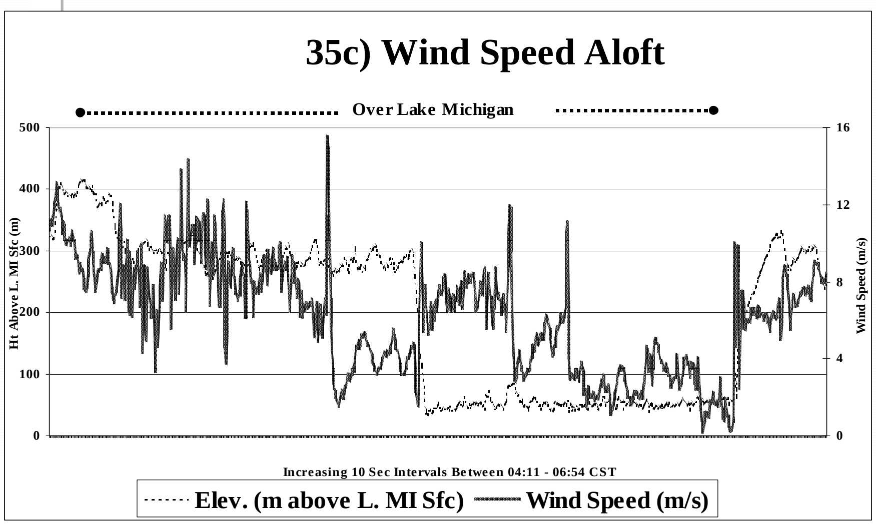
Similar to the dawn flight A on 6/23 (Fig. 25) -- the relatively high ozone (to 100 ppb) at approx. 300 m above L. Mich in the early daylight indicates that substantial ozone was carried over from 6/23. At the lower heights (about 50 m) above the Lake -- a lot of variations in ozone (30 -80+ ppb). This suggests that there were some areas near the Lake's surface where O3 was insulated from overnight destruction at the surface, and some areas were ozone might have been reduced by processes such as being titrated by early-morning NOx-rich plumes from power plants. Unlike the 6/22 and 6/23 flights, this path monitored relatively high ozone (90+ ppb) over land -- suggesting that 3 days into the episode the build up and carryover of ozone was extending to over land.

Figure 35: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight A
04:14 - 06:55 CST 24 June 02

The meteorological profiles monitored over the Lake during this early-daylight flight on 6/24 has similarities to those collected during Flight C on 6/23 (12:25-14:41 -- Fig. 29): At approx. 300 m above L. Mich there was fairly warm (to 27 C) and moderately moist (to 60% rel. hum.) air. With the plane's descent to 50 m heights came a decrease in temperature & increase in humidity, suggesting a shallow conduction inversion layer just above the Lake's surface (also seen in the 6/22 Flight B [Fig 13] and 6/23 Flight C [Fig 29]). Wind speeds at the 50 m heights were generally weak-to-moderate (2-8 m/s), indicating stagnating conditions -- favorable to enhancing ozone production rates (App. A). Note: The near-surface winds were westerly (off-shore IL & WI) -- indicating an early morning "land breeze" that was possibly transporting fresh (rush hour) ozone precursor emissions into the Lake's conduction inversion.







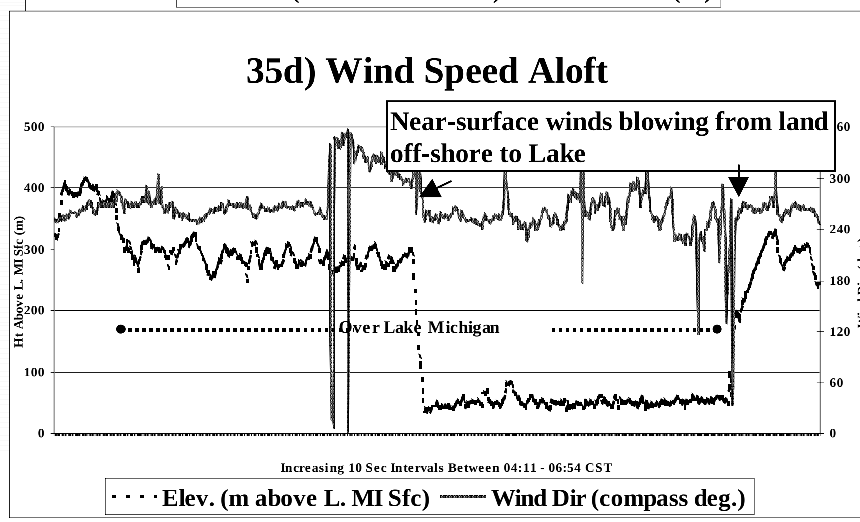
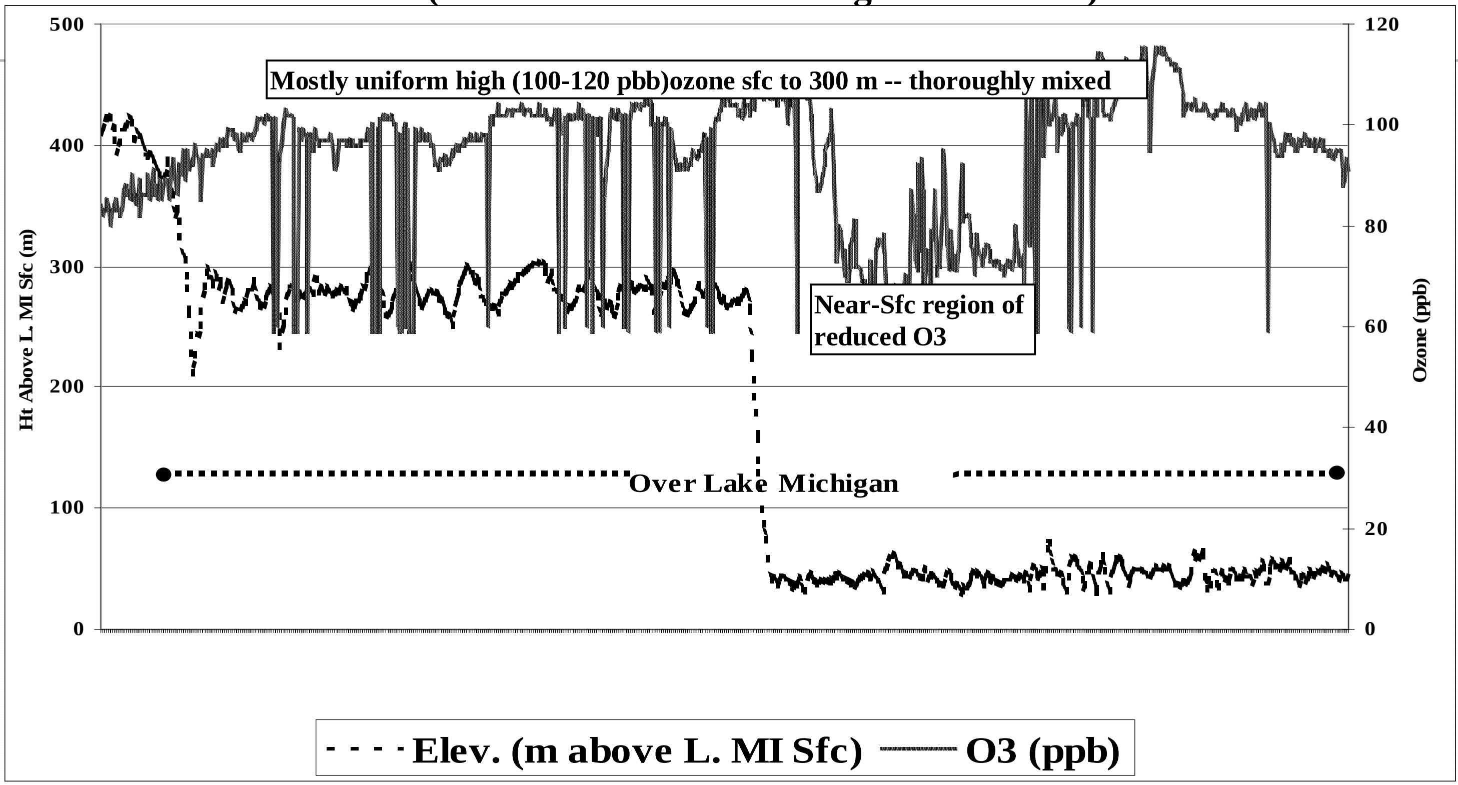


Figure 36: Time Series
Ozone & Height Above L. Mich Level
WDNR Monitoring Flight B
08:58 - 11:15 CST   24 June 02
(Note: there was no "C" flight on 24 June)



This mid-to-late morning Flight B on 6/24 measured ozone profiles that were similar to those collected during Flight A several hrs earlier (Fig. 34): However, the ozone levels at approx. 300 m above L. Mich increased modestly (about 20 ppb to total 110 ppb) relative to Flight A,. However, at the lower heights (50 m) above the Lake there was one region that had ozone levels at the same level as flight A(60 - 90 ppb highlighted in the graph) and another area that saw a considerable ozone jump (40-70 ppb) to values peaking at 115 ppb. The former region may have been titrated of ozone by a NOx-rich plume. However, no NOx measurement data exist to investigate that speculation. The zone of higher ozone near the Lake's surface suggests that both much new ozone and fresh morning precursors reacting into ozone had advected eastward through the Lake's lower atmospheric levels from the Chicago-Milwaukee region's rush hour activities and other areas further upwind.

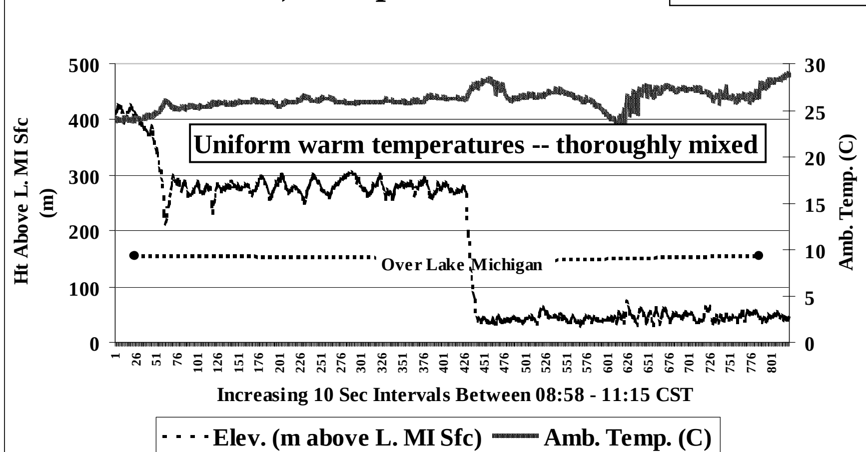
Figure 37: Time Series

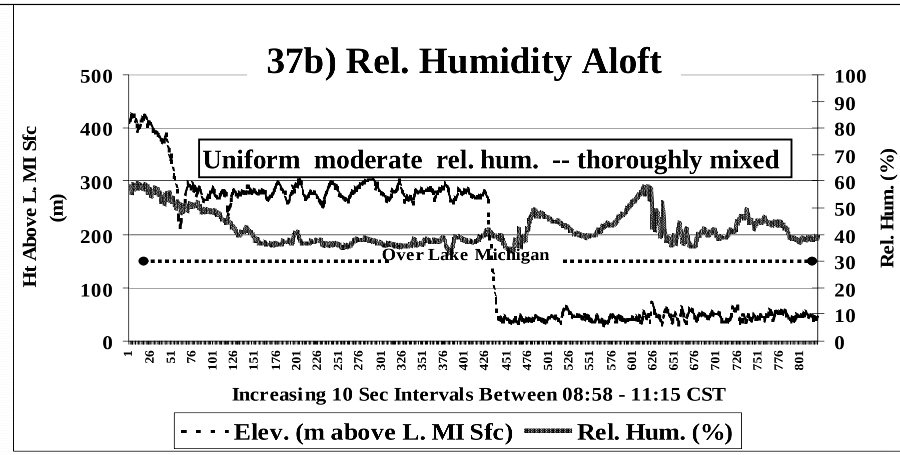
Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight B

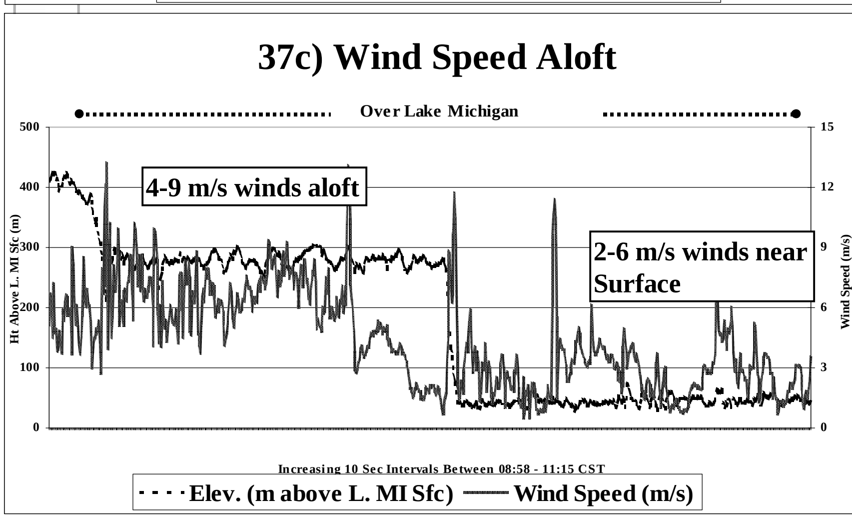
08:58 - 11:15 CST 24 June 02

The meteorological profiles measured during this mid-to-late morning Flight B bears some resemblance to those captured during the early afternoon Flight B on 6/23 (Figure 27): The air mass from 50 m up to 300 m above the Lake's surface was uniformly mixed with warm (27-28 C) & moderately humid (40-50% rel. hum.) air -- indicating the absence of a near-surface conduction inversion during this flight. The modest aloft wind speeds (4-9 m/s) were noticeably higher than near the surface, which often witnessed near-calm conditions. There was also wind directional shear in the vertical: approximately from 240-270º (offshore flow) aloft and largely variable near the surface. The near-surface flow shifted considerably from the steady wetserly (off-shore) pattern measured during Flight A (Fig. 35).

37a) Temperature Aloft







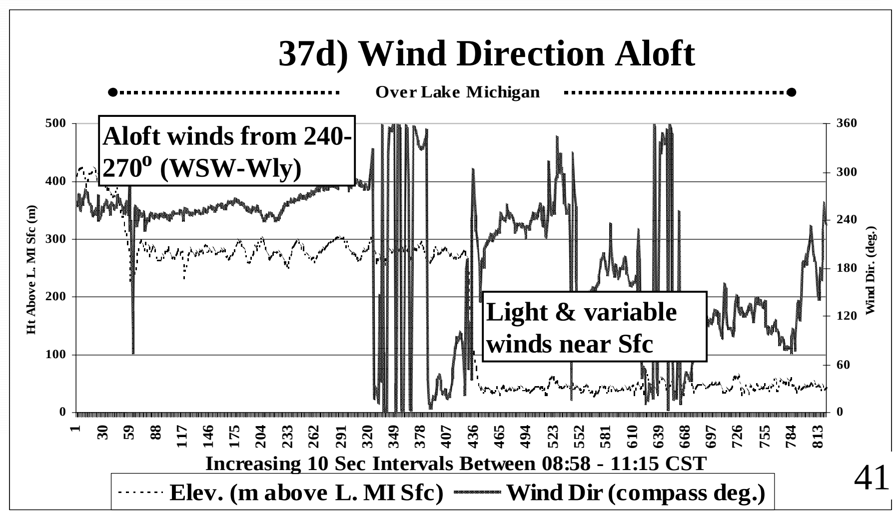
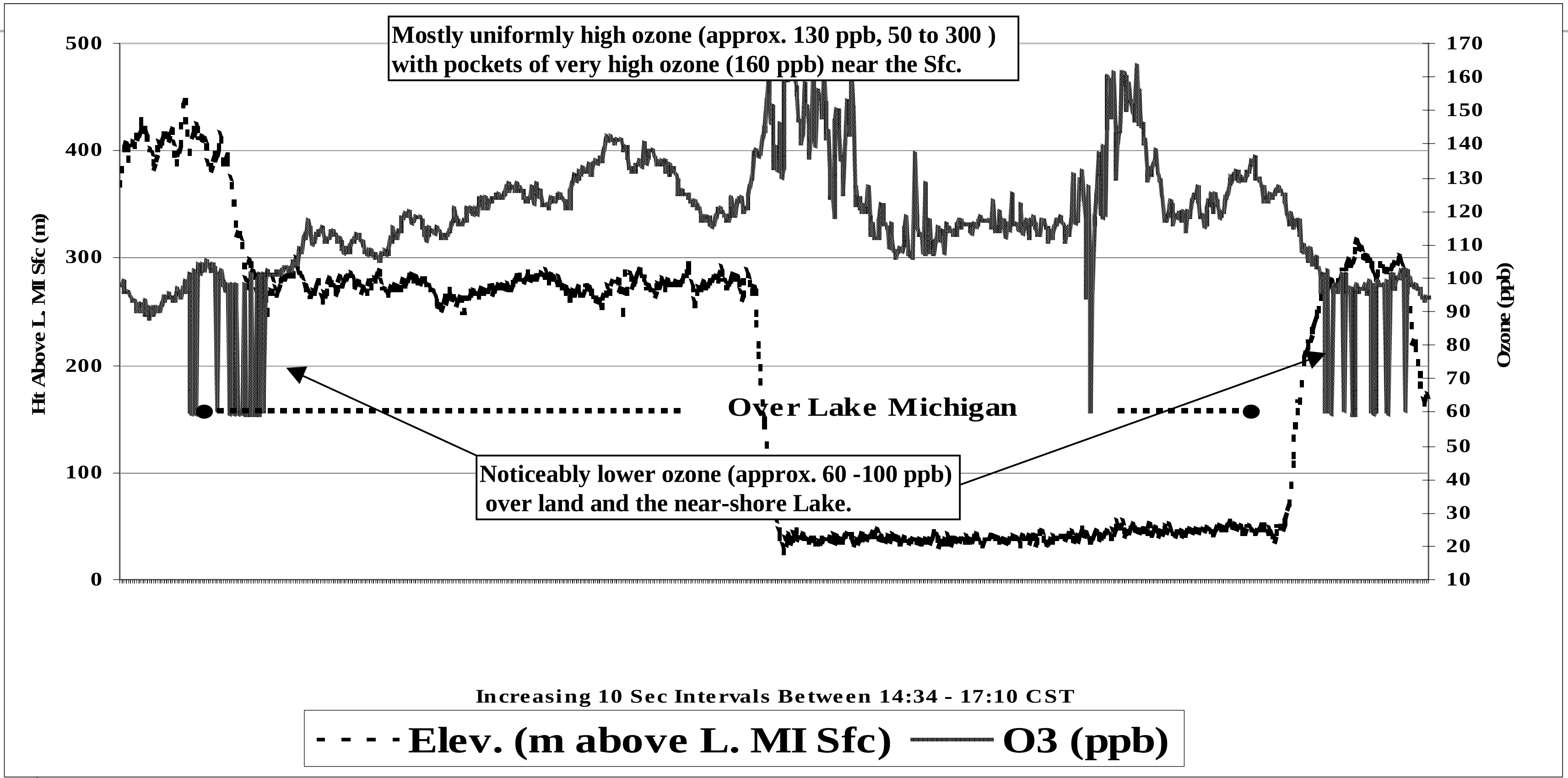


Figure 38:Time Series
Ozone & Height Above L. Mich Level
WDNR Monitoring Flight D
14:34 - 17:10 CST   24 June 02
(Note: no “C” flight on 6/24)



This mid-to-late afternoon flight measured ozone levels that were still quite high (110 - 160 ppb) from the surface to 300 m over the Lake -- suggesting that the ozone was well mixed in the vertical during this afternoon period. Over the land the ozone was slightly less (approx. 100 ppb). As in Figures 16 and 28, the declining ozone over both land and the near-shore Lake suggest that conditions ideal for producing ozone were much better over the Lake’s interior areas compared to over the near-shore Lake or on land.

Figure 39: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight D 14:34 - 17:10 CST 24 June 02

This mid-to-late afternoon Flight D strongly resembles that for Flight D on 6/22 (Fig 20): Measuring an air mass from 50 m to 300 m above the Lake's surface that was mostly thoroughly mixed with warm (27-28 C) & moderately humid (40-50% rel. hum.) air -- indicating the absence of a near-surface conduction inversion during this flight. As also with 6/22's flight D -- there appeared to be a brief conduction inversion zone (lower temps, increased humidity) near the Wis coast north of Milwaukee. The aloft wind speeds were mostly light (less than 5 m/s) and variable -- and noticeably lower than near the surface, which had on-shore flow -- advecting ozone towards the land -- a decoupling in the flow between the higher and lower levels over the Lake.

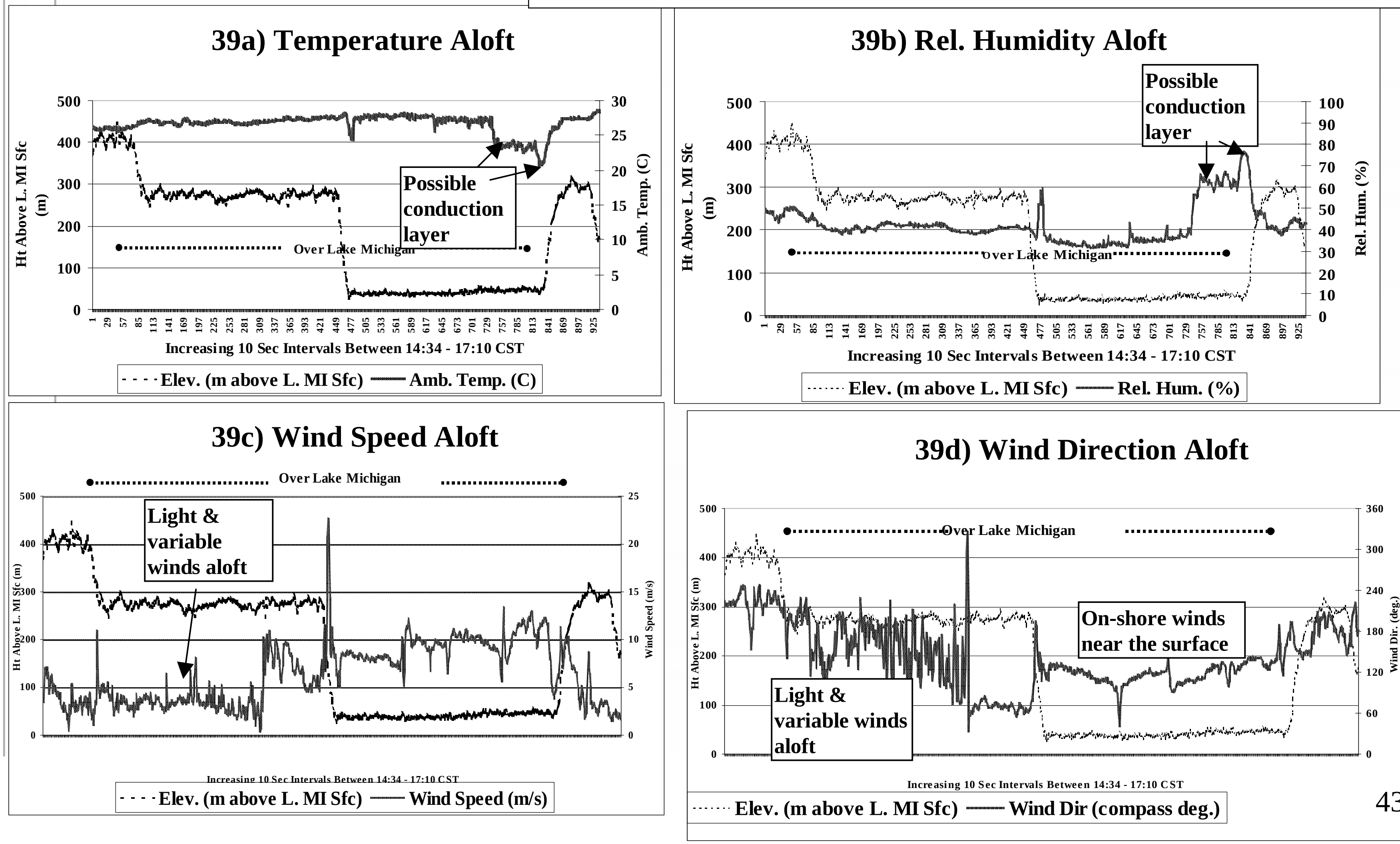


Figure 40: Ozone Aloft

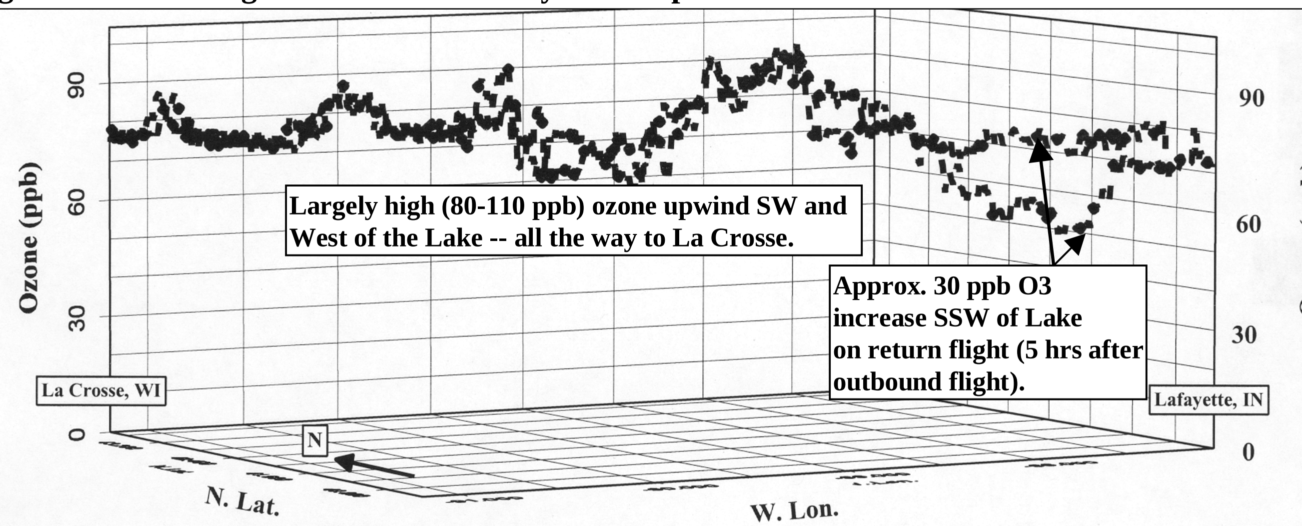
RB Jacko L. Mich. "Boundary" Flight

Monday, 24 June 02

Westbound: Lafayette, IN - La Crosse, WI 11:17 - 13:37 CST

Eastbound: La Crosse - Lafayette 13:37 - 16:12 CST

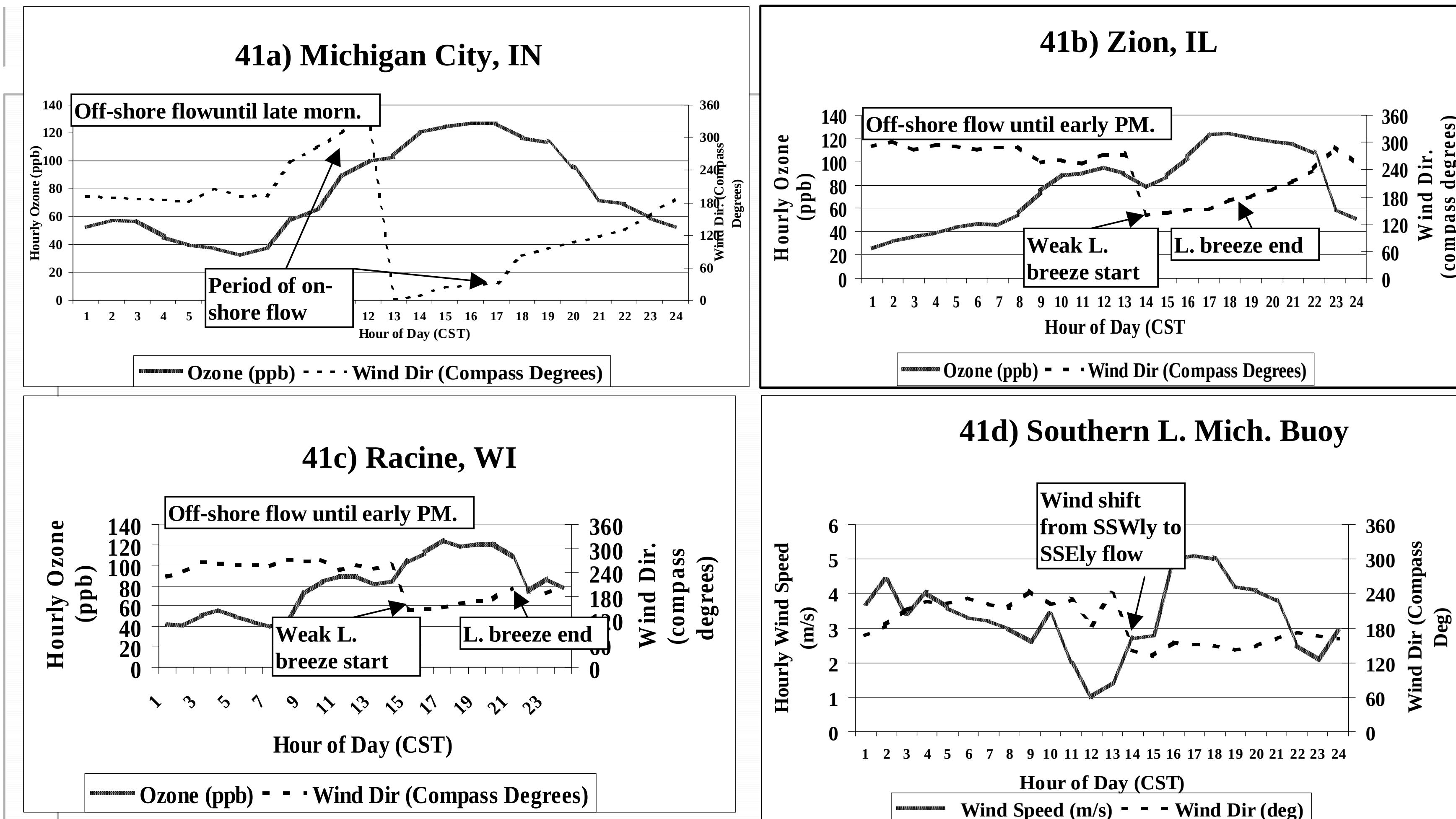
As with the RB Jacko boundary flights on 6/22 (Fig. 21) & 6/23 (Fig. 30) -- the ozone was mostly uniform through the vertical, despite the up-and-down element in the airplane's path trajectory (see Fig. 5) during both legs of the flight. This again indicated that the ozone was well-mixed vertically in this over-land region. Relative to 6/23, this area of high aloft ozone (80-100 ppb) continued to expand farther west of the Lake. This is an increase in the geographical region of high ozone aloft considered background and incoming to L. Mich. This indicates that the influence of meteorological conditions favorable to ozone production were still spreading farther in the region on the 4th full day of this episode.



Ozone measurements (10 second averages) were taken at heights varying between 70 and 900 meters above the average elevation of the L. Michigan surface, which is approximately 170 m above mean sea level. According to Prof. Jacko, the original ozone data are perceived to be 1/2 the true value. Consequently, each individual ozone point displayed here is twice what was originally logged.

Figure 41: Time Series -Hrly Surface Data - 24 June 02

A) Michigan City, IN B) Zion, IL & C) Racine, WI: Ozone & Wind Dir.
D) Southern L. Mich. Buoy: Wind Speed & Direction

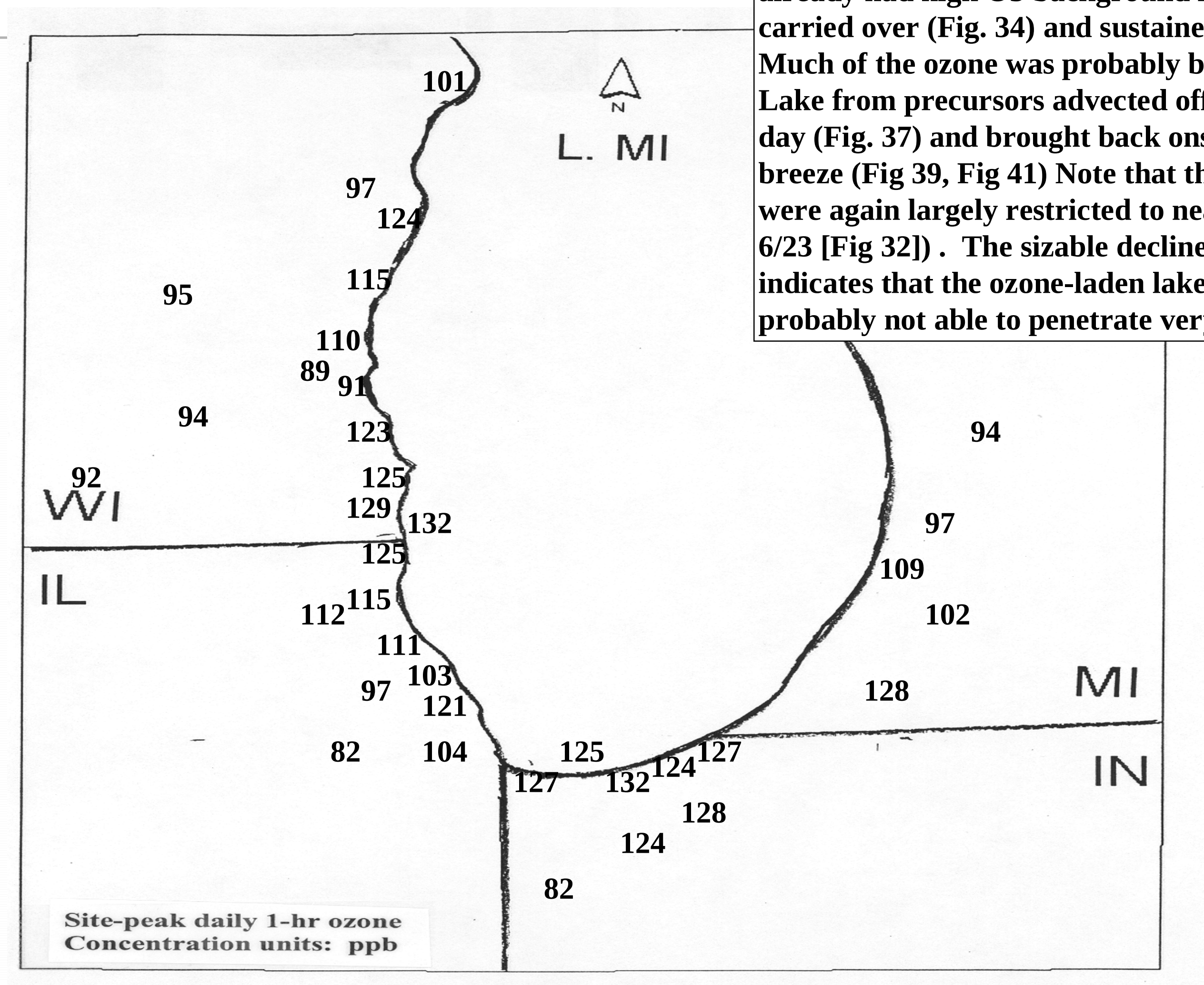


<u>6/24/02 surface</u>: **Mich. City, Zion & Racine all witnessed moderately on-shore flow during the afternoon. In this 4th day of the episode, all 3 sites monitored high ozone (approx 120 ppb) that was less (15-20 ppb) than on 6/23 (Fig. 31). The Lake buoy saw mostly modest (3-5 m/s) SSWly-to-SSEly surface flow. This indicates that the central part of Southern L. Mich continued to be dominated by the surface high pressure system in the Eastern U.S..**

Figure 42

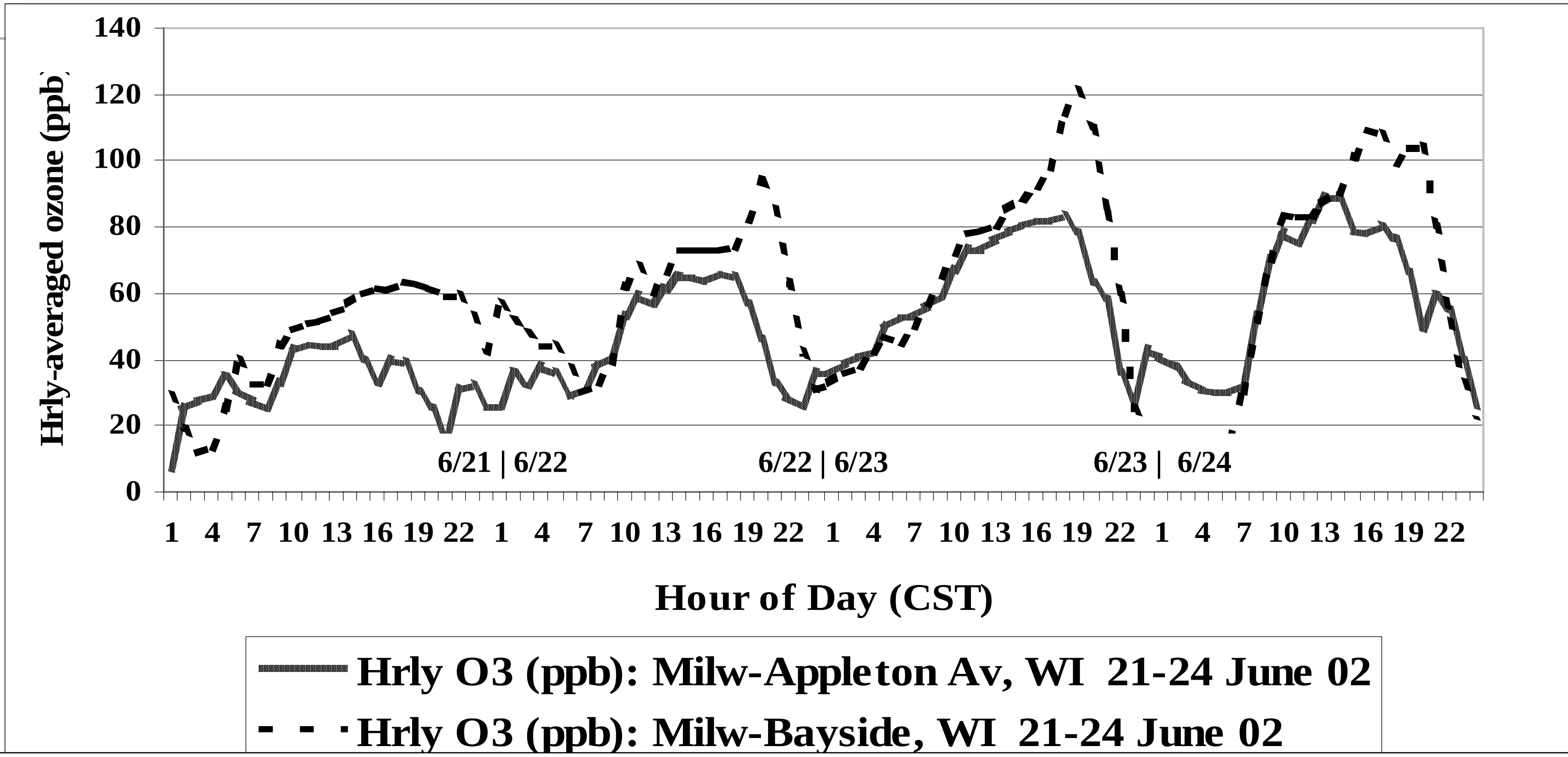
Site Peak-Daily 1-Hr Ozone (ppb)
Monitoring Sites in the S. Lake Mich. Area

24 June 02 (Monday)



<u>6/24/02 Peak surface ozone:</u> In general, the 6/24 peak ozone map resembles that for 6/23 (Fig. 32). Namely, the high shoreline ozone reflects being in the 4th day of an episode that was being dominated by a surface high pressure system situated in the Eastern USA that pumps warm, stagnant, hazy air into a region that already had high O3 background levels (100 ppb+) carried over (Fig. 34) and sustained aloft (Fig. 40). Much of the ozone was probably being formed over the Lake from precursors advected off-shore earlier in the day (Fig. 37) and brought back onshore by the lake breeze (Fig 39, Fig 41) Note that the high ozone levels were again largely restricted to near-shore sites (like 6/23 [Fig 32]) . The sizable decline in ozone inland indicates that the ozone-laden lake breeze front was probably not able to penetrate very far onshore.

Figure 43a: Time Series -- Hourly Ozone
Milwaukee-Appleton Ave (10 km west of L. Mich)
Milwaukee-Bayside (2 km west of L. Mich.)
21 - 24 June 02 (Fri-Mon)



This display graphically shows that the daytime ozone concentrations declined considerably at inland sites as close as 10 km from L. Mich (e.g., Milw-Appleton Ave.) relative to the near-shore sites such as Milw-Baside. The "App Av" site witnessed mostly southwesterly (offshore direction) winds (see Fig. 43b). The near-shore site at Bayside actually did not see a defined lake breeze during the episode. However, it did record calm winds (wind speeds less than about 1.5 m/s [the anemometer's minimum detectable limit]) for 51 of the 96 hours during 21 - 24 June (Fig. 43b). The calm winds (stagnant air) are considered favorable to ozone formation. Furthermore, the Bayside calm winds suggest that perhaps a very weak lake breeze (i.e., less than 1.5 m/s -- undetectable) might have occasionally penetrated to the site during some of the afternoon calm periods. The lake breeze is typically a relatively weak wind regime (Appendix A).

Figure 43b

Time Series: Hourly Wind Direction
Milwaukee-Appleton Ave (10 km west of L. Mich)
Milwaukee-Bayside (2 km west of L. Mich.)
21 - 24 June 02 (Fri-Mon)

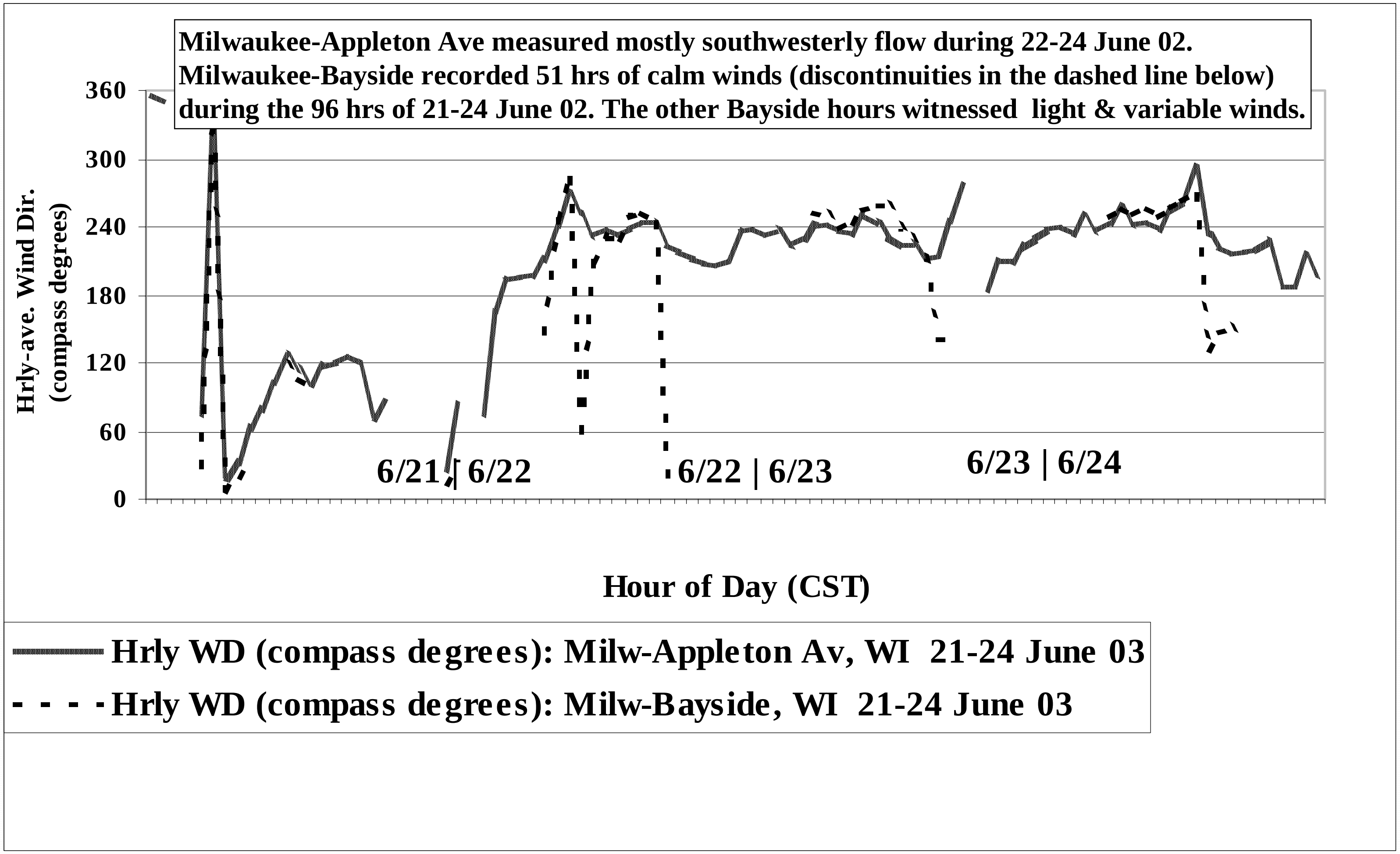
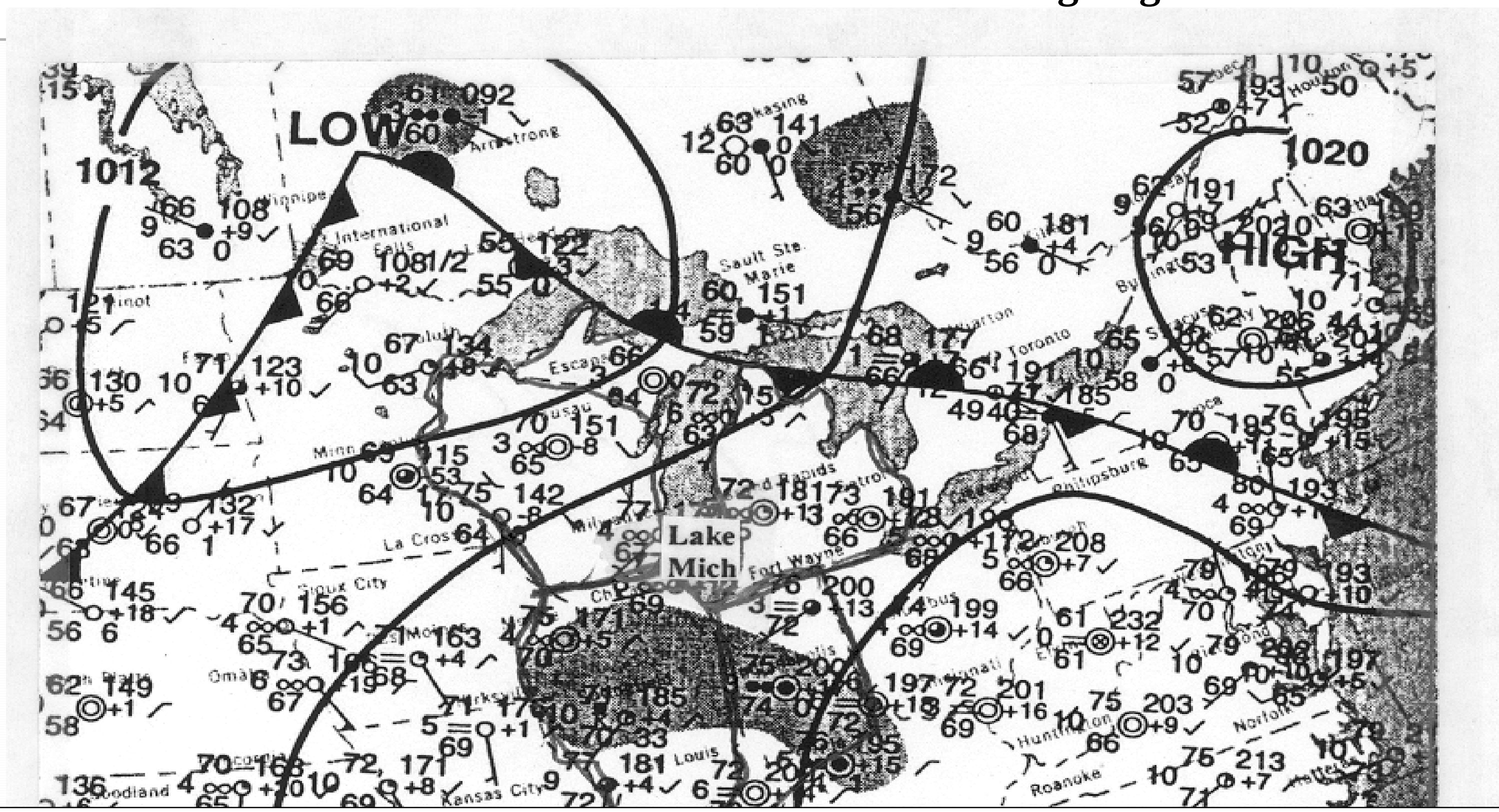
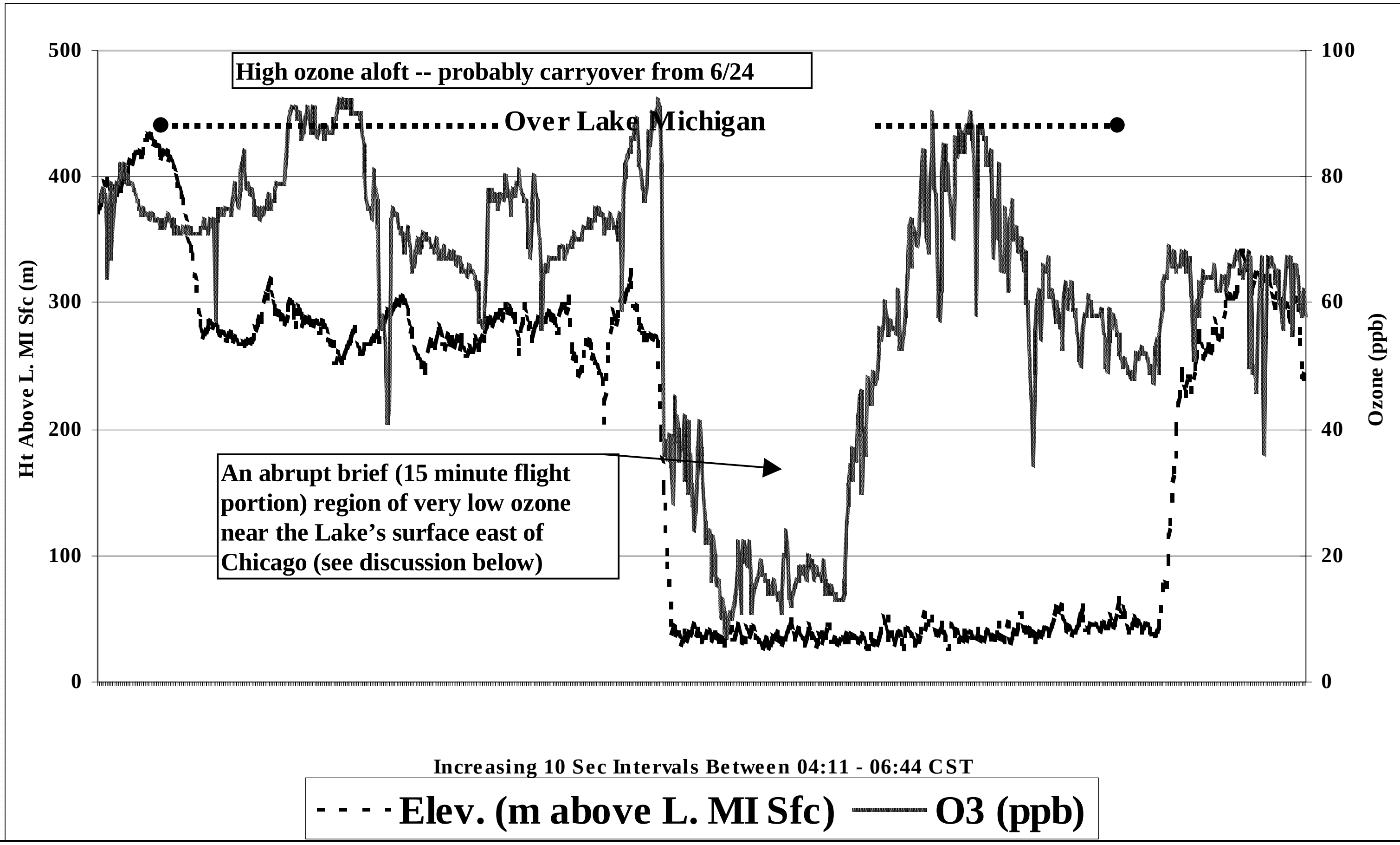


Figure 44
Surface Synoptic Weather Map
6 AM CST 25 June 02
(Tuesday -- Episode Day 5, End of Episode)
4 WDNR & 1 RB Jacko Monitoring Flights



<u>6/25/02 Lake Mich. area surface synoptic meteorology:</u> The eastern high pressure system has degraded considerably. Non-frontal cloud activity has developed in northern Illinois and Indiana by 6 AM CST (dark areas on the map). Apparently this cloud system advected northward, resulting in clouds and rain hitting Michigan City by noon CST. Milwaukee witnessed overcast skies by 1300 CST. Western Michigan (i.e., Muskegon) still had warm (26 C), humid (dew points to 22 C) and hazy skies on 6/25. However, the weather upwind of this region had clouds and rain -- not conducive to producing excessive levels of ozone that could be transported northeastward across the Lake to Muskegon.

Figure 45:Time Series
Ozone & Height Above L. Mich Level
WDNR Monitoring Flight A
04:11 - 06:22 CST 25 June 02

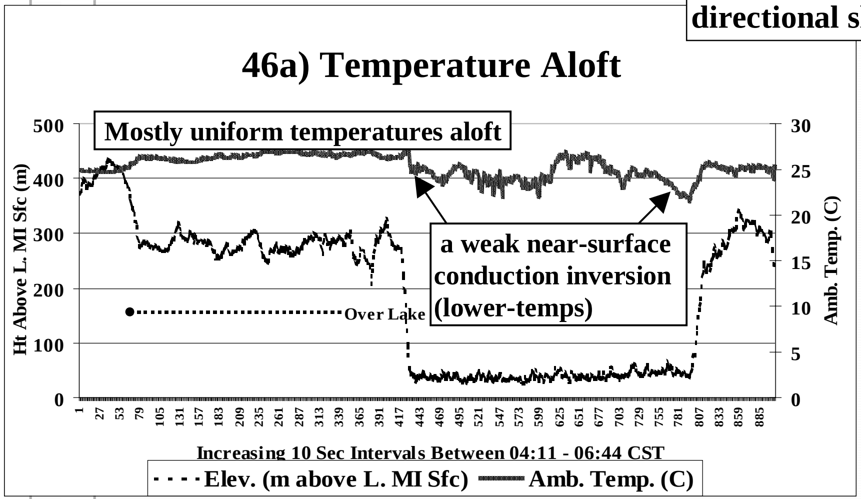


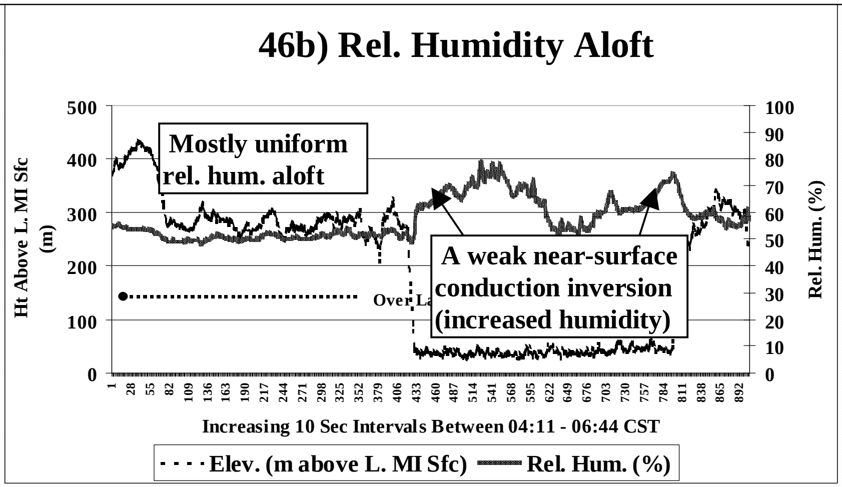
The region of very low ozone near the surface above the Lake and east of Chicago (Figure 3) is not explained by the aloft meteorological measurements (Fig. 46). It could be speculated that this area had low ozone due to any of several reasons: no carryover from the day before, ozone destroyed due to mixing impaction to the Lake's surface, titrated out in a NOx-rich plume that advected offshore from land-based emission sources. A lack of aircraft NOx measurements makes it difficult to test the NOx plume hypothesis. However, the strong recovery to 100 ppb ozone levels gives the the NOx plume scenario some credibility.

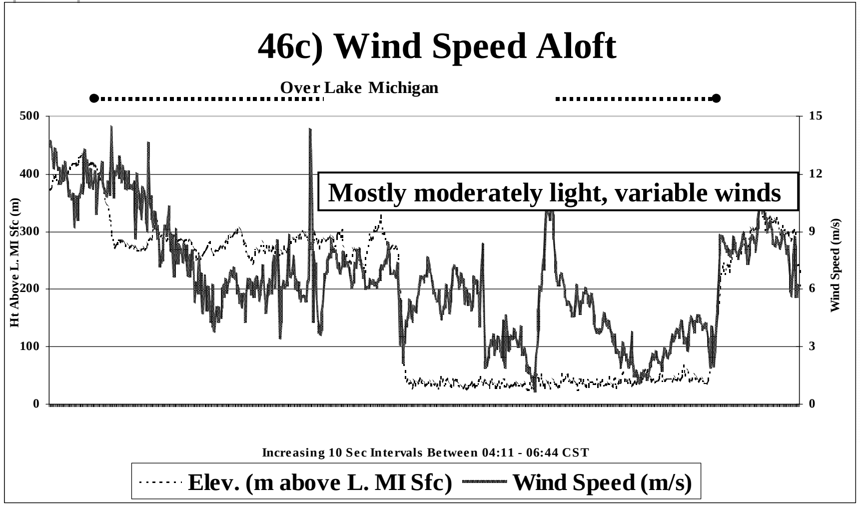
Figure 46: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight A

04:11 - 06:44 CST 25 June 02

The meteorological profiles monitored over the Lake during this early-daylight flight on 6/25 has similarities to those collected during Flight A on 6/24 (04:14-06:55, Fig. 35): At approx. 300 m above L. Mich there was fairly warm (to 27 C) and moderately moist (to 60% rel. hum.) air. With the plane's descent to 50 m heights came a slight decrease in temperature & increase in humidity, suggesting a weak conduction inversion layer just above the Lake's surface. Wind speeds at 300 m heights were generally weak-to-moderate (2-8 m/s), and at 50 m levels -- almost calm winds, indicating stagnating conditions -- favorable to ozone production (App. A). However, unlike 6/22 Flight B (Fig. 13) & 6/23 Flight C (Fig. 29) -- there was hardly any directional shear in the westerly-northwesterly (off-shore) winds vertically.







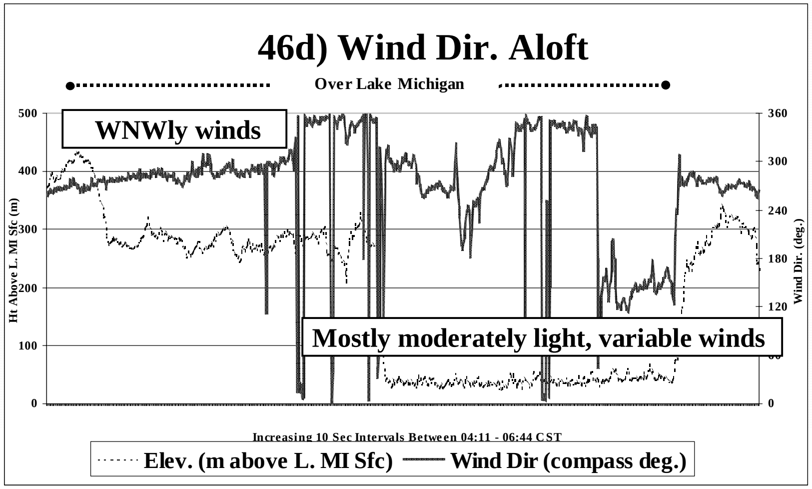
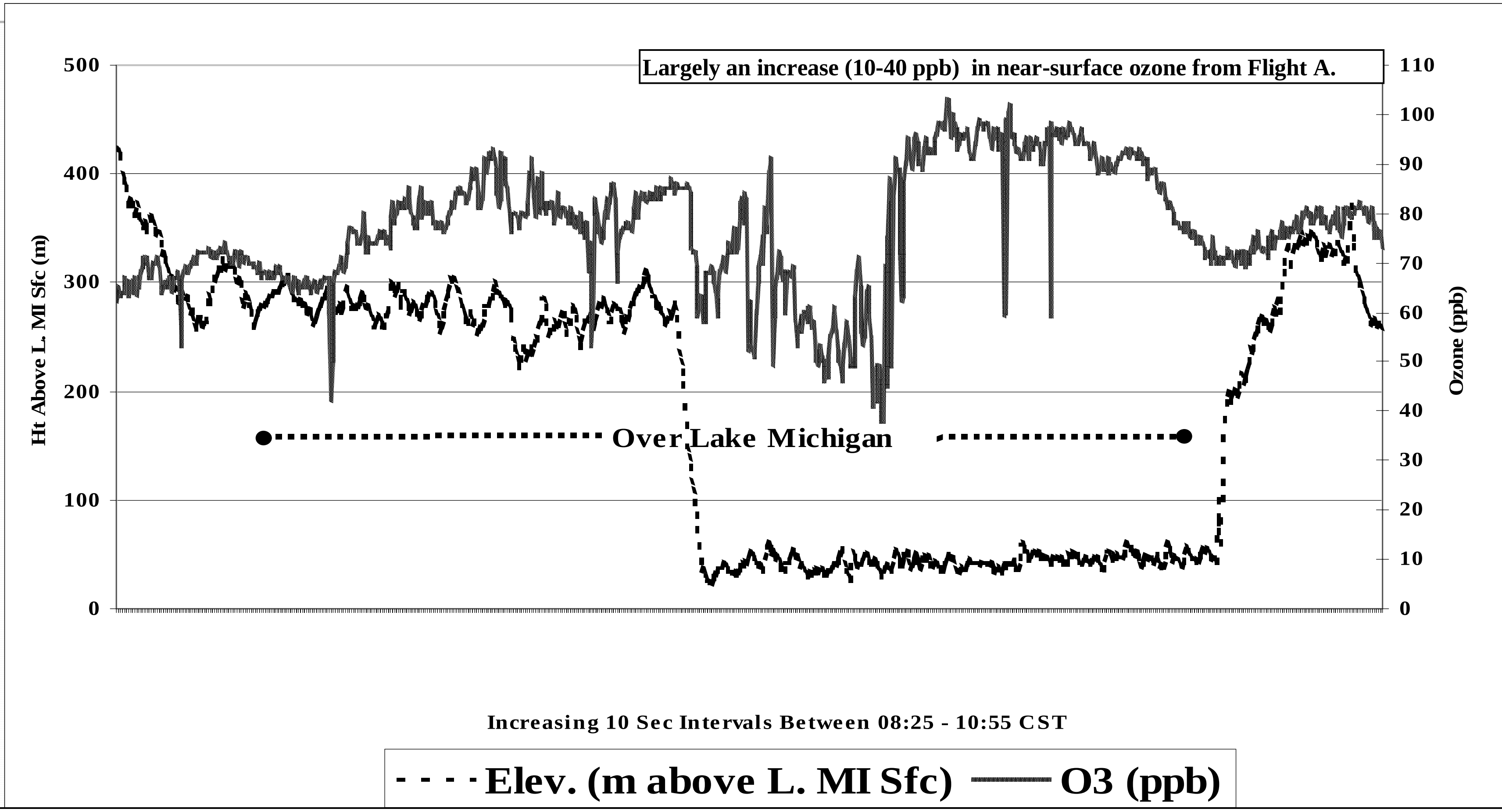


Figure 47: Time Series
Ozone and Height Above L. Mich Level
WDNR Monitoring Flight B
08:25 - 10:56 CST   25 June 02



The ozone profile measured during this mid-morning Flight B appears to be a modified yet similar to that taken 4 hours earlier during Flight A (Fig 45) -- including a much less-pronounced ozone "hole" near the Lake's surface east of Chicago. The peak ozone levels had increased a modest 5-10 ppb from Flight A.

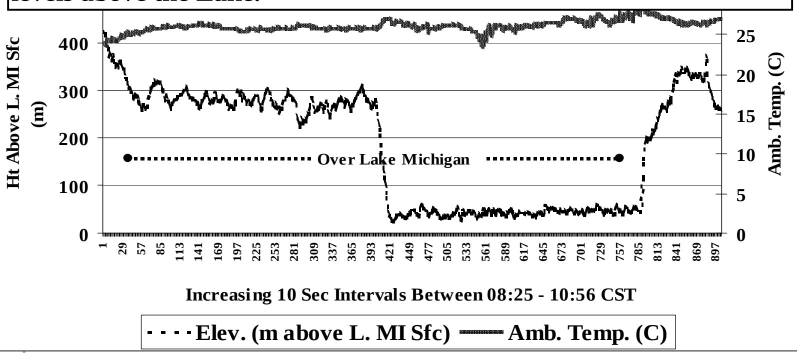
Figure 48: Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight B

08:25 - 10:56 CST 25 June 02

This mid-to-late morning Flight B measured an air mass throughout the lowest 300 m above southern L. Mich. that was largely homogeneous in temperature and moisture, with moderate winds aloft and very calm winds near the surface. Any evidence of a conduction inversion was absent here -- after a weak one was noted in Flight A (Fig. 46).

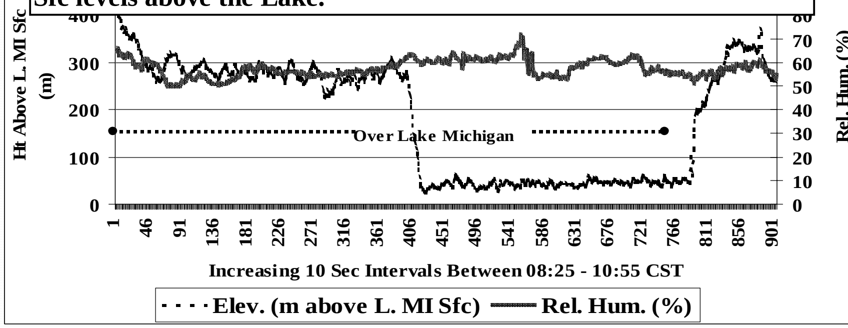
48a) Temperature Aloft

Uniform warm (25 C) temperatures through both aloft and near-Sfc levels above the Lake.



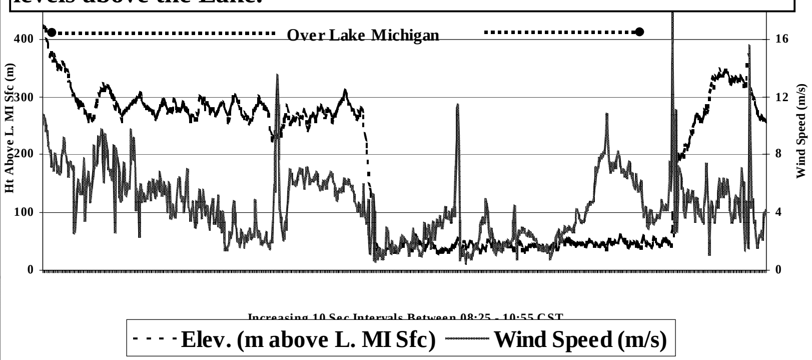
48b) Rel. Humidity Aloft

Uniform moderate (50-60%) rel. hum. through both aloft and near-Sfc levels above the Lake.



48c) Wind Speed Aloft

Mostly light winds (less than 8 m/s) through both aloft and near-Sfc levels above the Lake.



48d) Wind Dir. Aloft

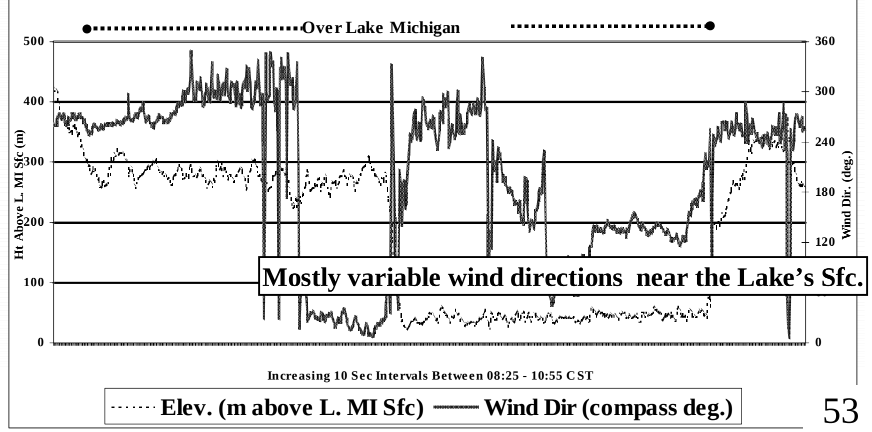
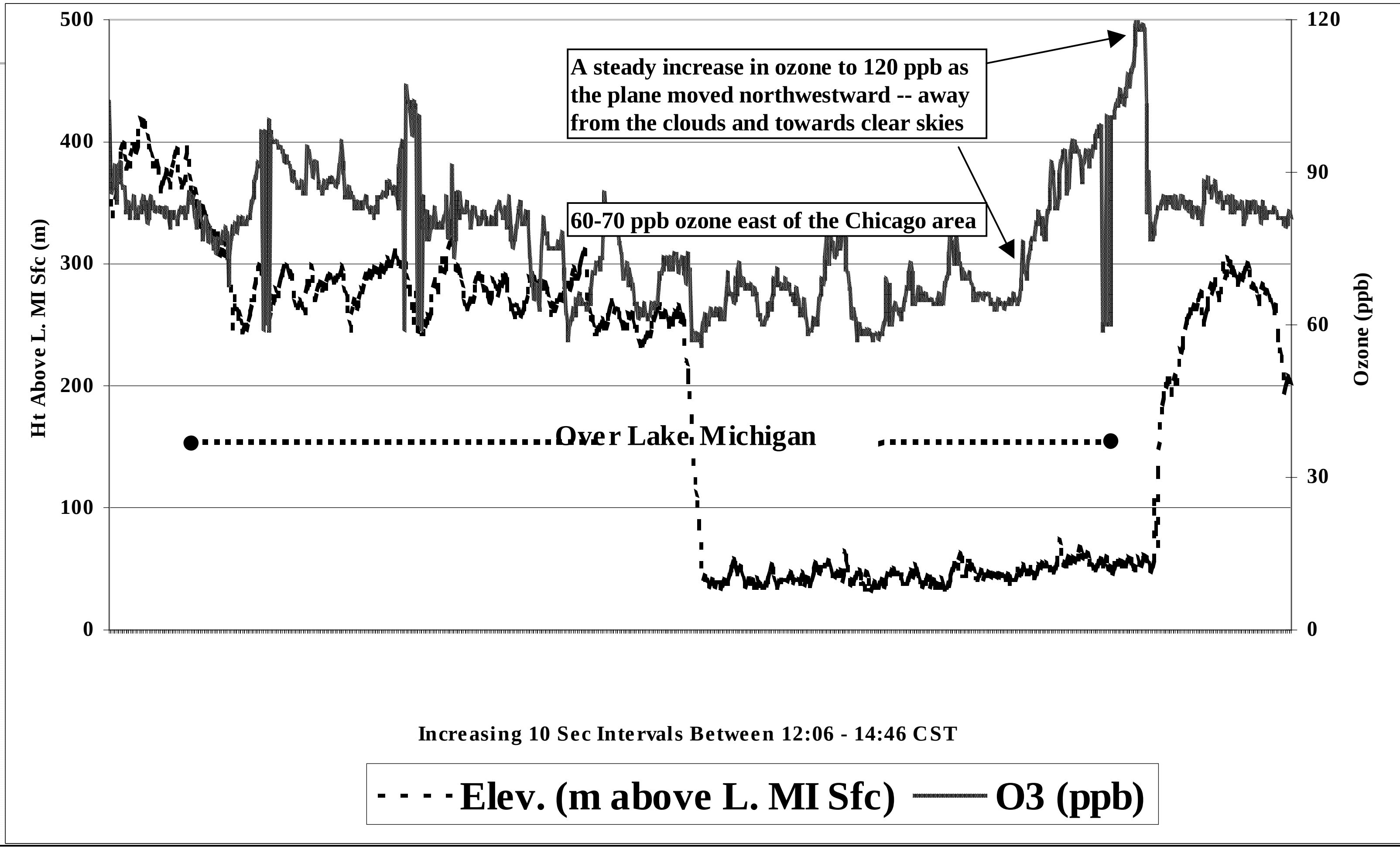


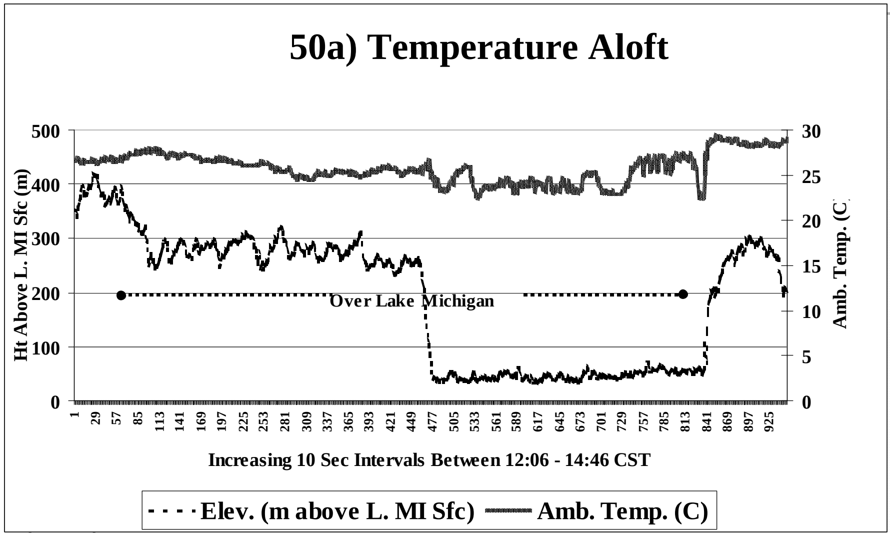
Figure 49: Time Series
Ozone and Height Above L. Mich Level
WDNR Monitoring Flight C
12:06 - 14:46 CST   25 June 02

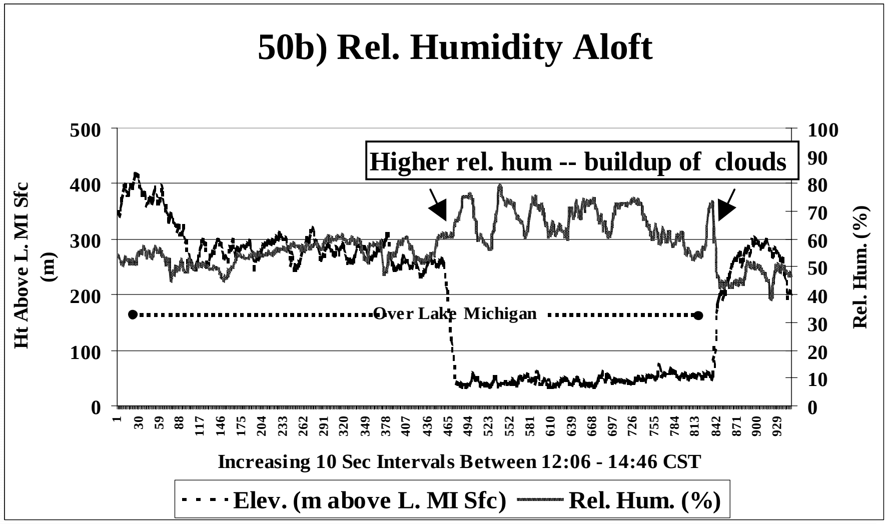


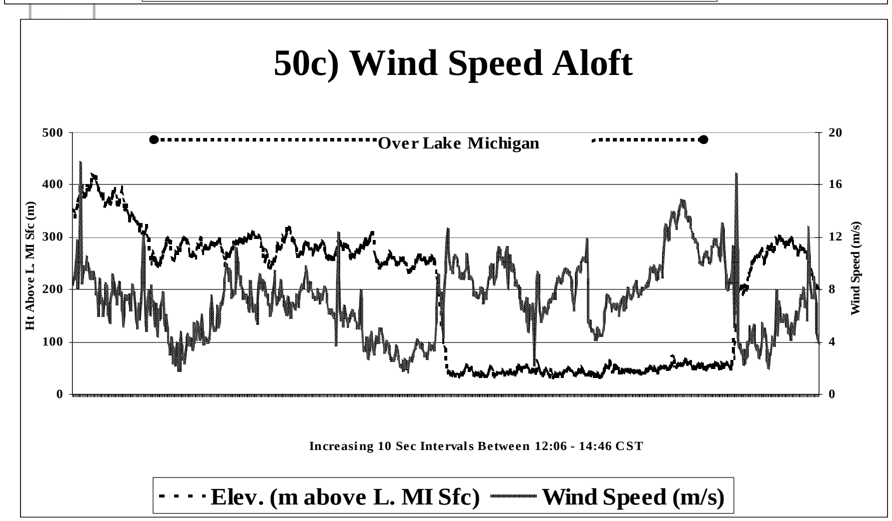
There was a wide variation in the ozone measured during this early-to-mid afternoon Flight C, especially in the 50 m height layer -- ranging from 60 ppb to 120 ppb. The minimum O3 was monitored off the coast of NE Illinois / SE Wis -- which was witnessing a buildup in clouds during this period (Fig 44). The 100 ppb+ ozone was measured over the Lake north of the Milwaukee coast, which was still largely cloud free at that time.

Figure 50: Time Series
Meteorological Measurements & Height Above L. Mich.
WDNR Monitoring Flight C
12:06 - 14:46 CST   25 June 02

This early-to-mid afternoon Flight C monitored still-warm (25-28 C), largely uniform air over the Lake. The rel. humidity, from Flight B (Fig 48), increased about 20% east of Chicago, reflecting the buildup of clouds in that area at that time. Winds over all levels of the Lake increased in speed and became more southerly during this flight relative to Flight B.







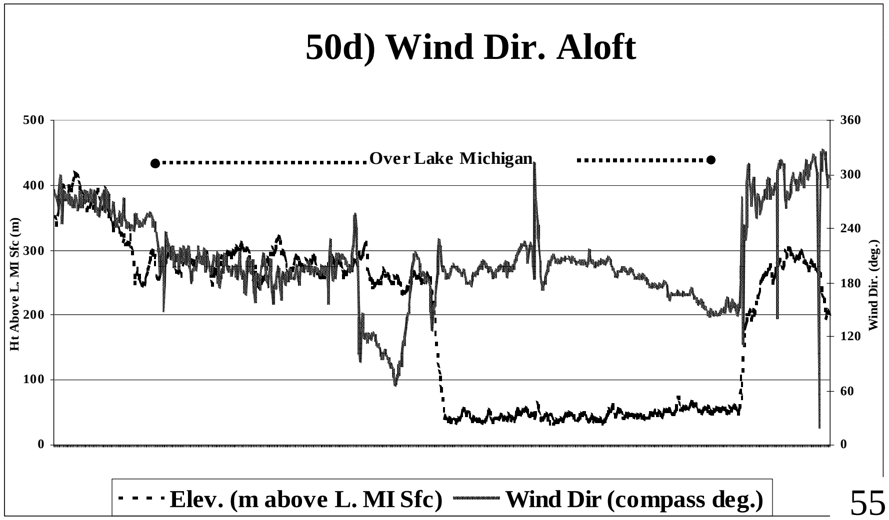
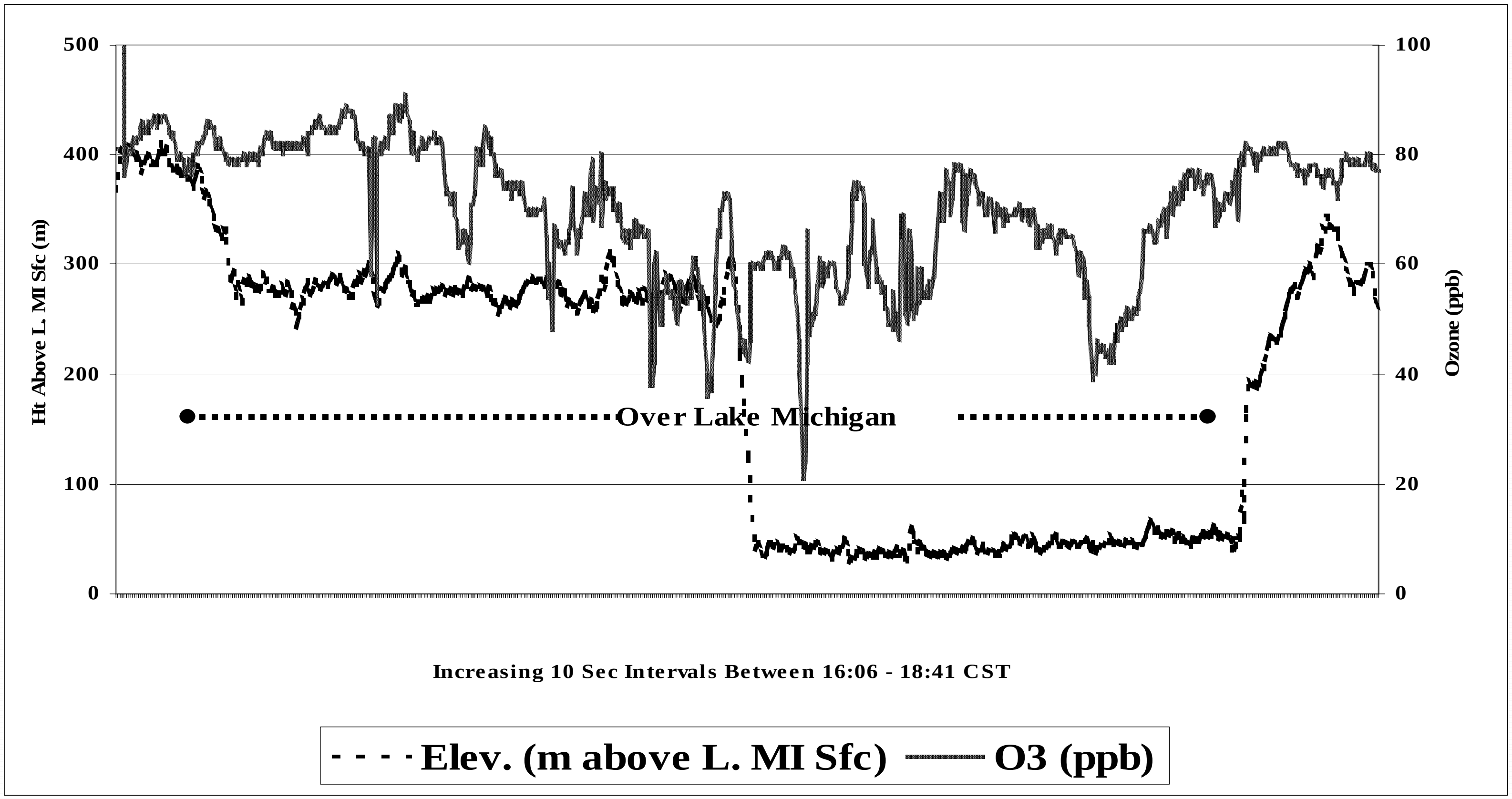


Figure 51: Time Series
Ozone and Height Above L. Mich Level
WDNR Monitoring Flight D
16:06 - 18:41 CST   25 June 02

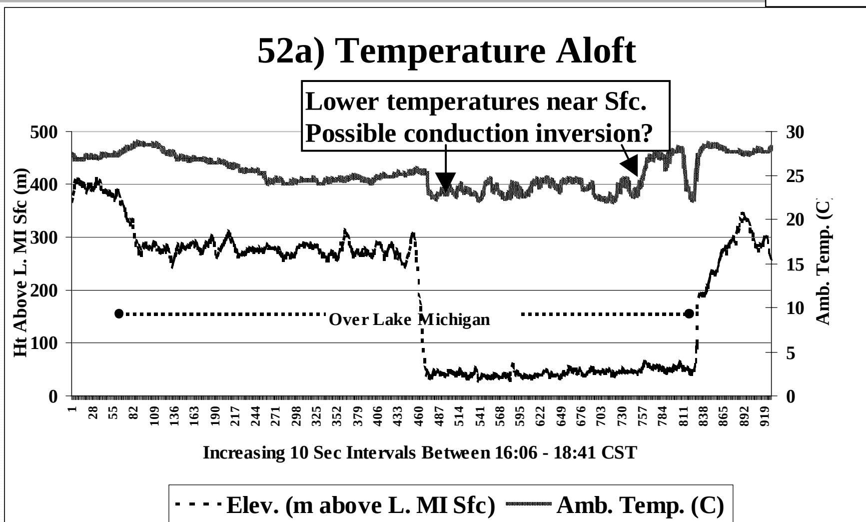


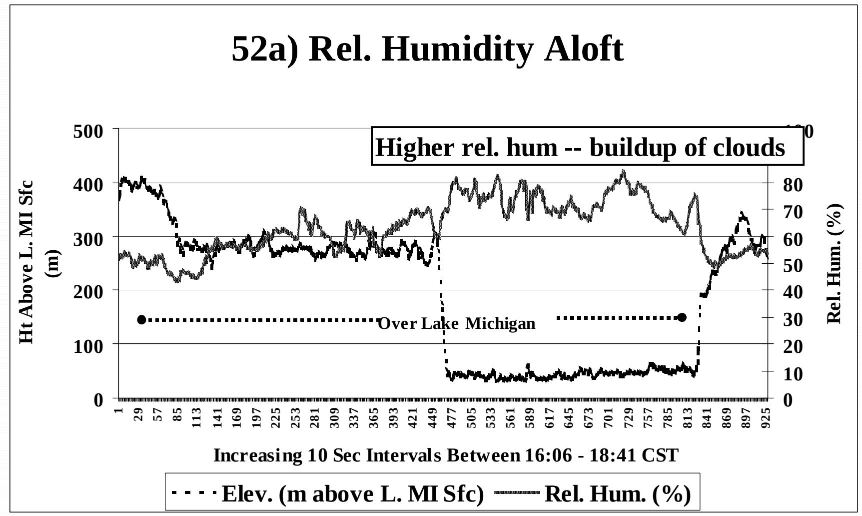
During this late-afternoon-early evening Flight D (the last WDNR monitoring flight of the episode) ozone levels decreased 10-30 ppb from Flight C (4 hrs earlier, Fig. 49). This feature suggests that the increasing cloud cover over the Lake was suppressing the solar radiation needed to photo-chemically generate ozone. Such ozone production had been very high during other Flight Ds in this episode (6/22 [Fig 19], 6/24 [Fig 38]) -- indicating that photo-chemistry can be optimized over the Lake during this time of the day under warm hazy skies with weak winds and negligible mixing. This display shows that when just one of the atmospheric conditions necessary for generating high ozone (i..e, abundant solar radiation [no clouds]) is missing -- ozone levels can substantially decrease.

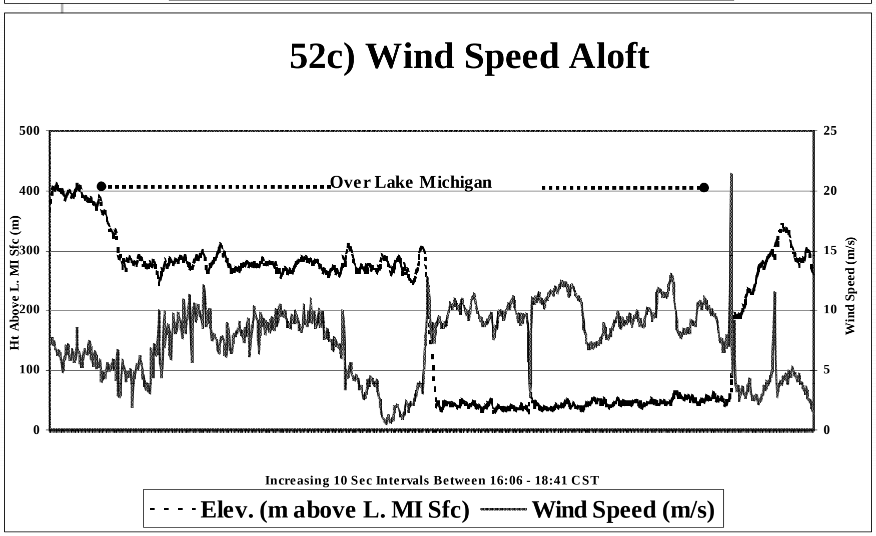
Figure 52:Time Series Meteorological Measurements & Height Above L. Mich. WDNR Monitoring Flight D

16:06 - 18:41 CST 25 June 02

This late-afternoon-early evening Flight D witnessed meteorological fields that are similar to those measured during Flight C (4 hours, Fig 50). However, a decrease in the temperatures near the surface suggest the reappearance of the conduction inversion. There has been an increase in rel. humidity compared to Flight C -- indicating an increase in both the amount and geographical extent of clouds over southern L. Michigan during this flight.







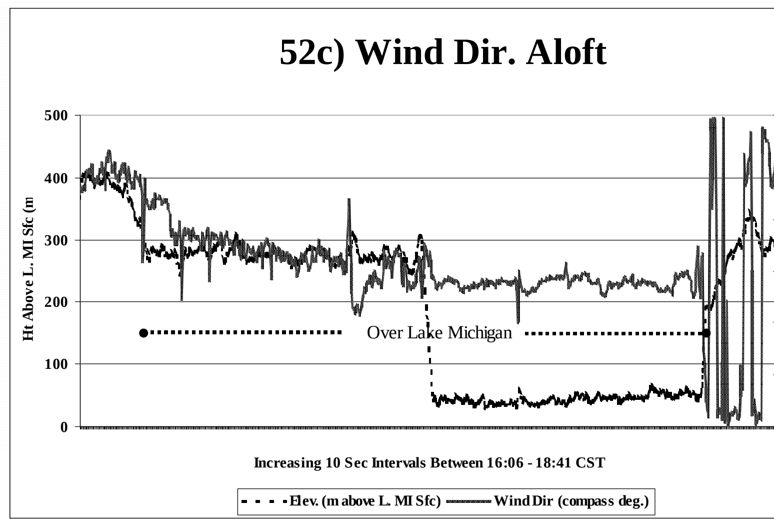
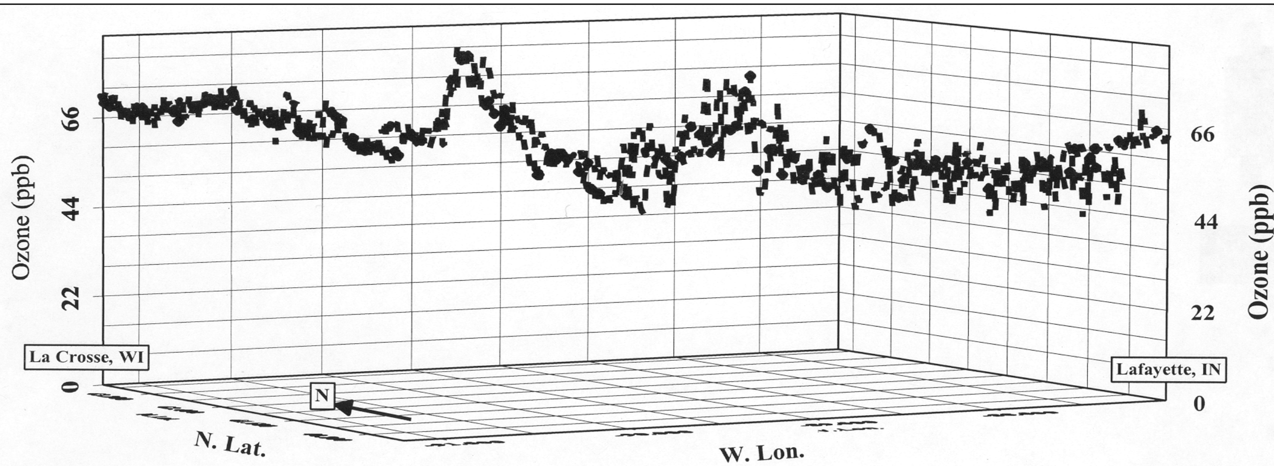


Figure 53

Ozone Aloft
RB Jacko L. Mich. "Boundary" Flight
Tues., 25 June 02
Westbound: Lafayette, IN - La Crosse, WI 11:05 - 13:25 CST
Eastbound: La Crosse - Lafayette 13:25 - 15:45 CST

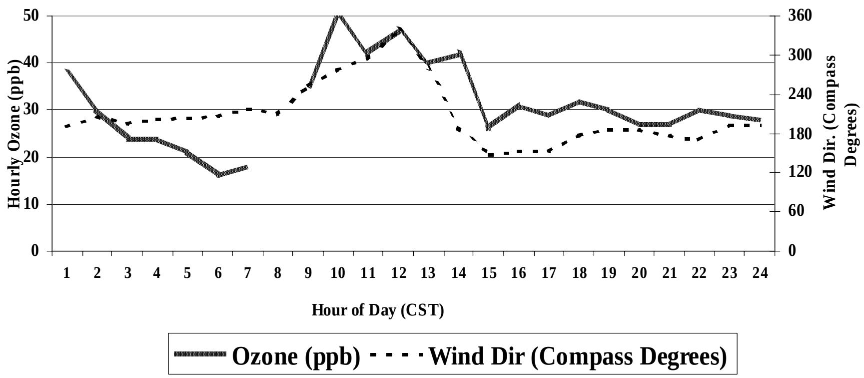
This final RB Jacko boundary flight of the ozone episode measured substantially less ozone (peaks around 70 ppb) than during previous flights (e.g., 6/24 [Fig. 40, peaks to 100 ppb]). It is likely that the airplane encountered much ozone-suppressing cloud activity during this flight -- both from the cloud deck south of L. Mich and an eastward-moving cold front from the west (Fig. 44).



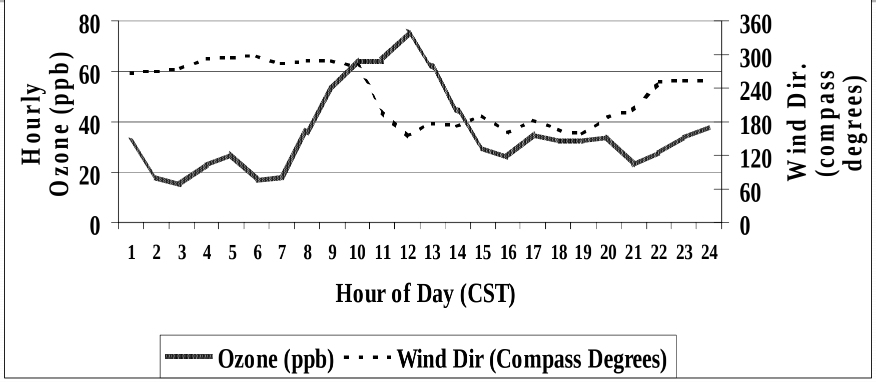
Ozone measurements (10 second averages) were taken at heights varying between 70 and 900 meters above the average elevation of the L. Michigan surface, which is approximately 170 m above mean sea level. According to Prof. Jacko, the original ozone data are perceived to be 1/2 the true value. Consequently, each individual ozone point displayed here is twice what was originally logged.

Figure 54: Time Series -Hrly Surface Data - 25 June 02
A) Michigan City, IN B) Zion, IL & C) Racine, WI: Ozone & Wind Dir.
D) Southern L. Mich. Buoy: Wind Speed & Direction

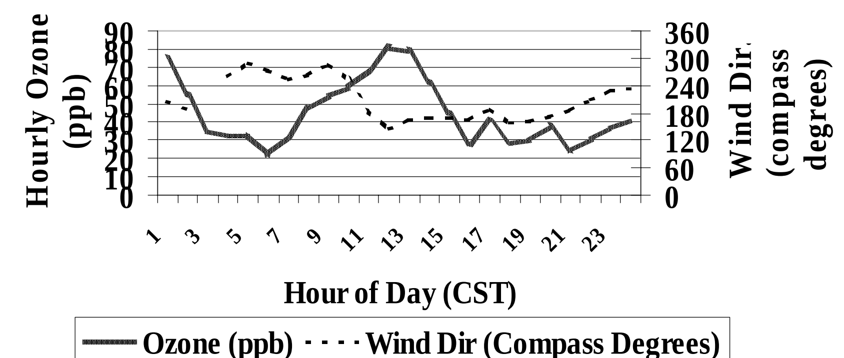
54a) Michigan City, IN



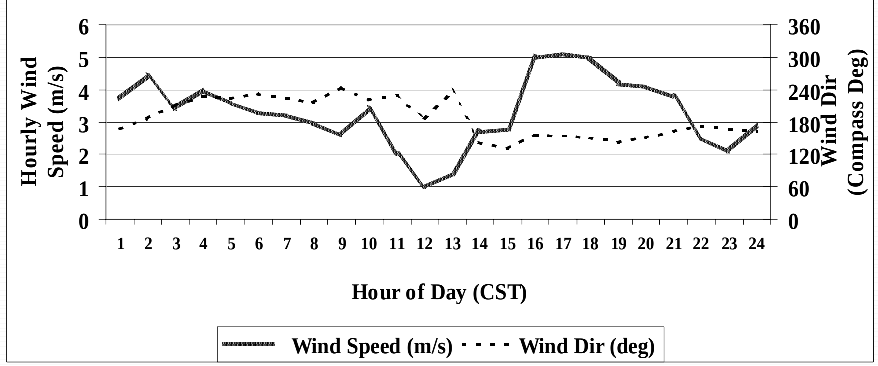
54b) Zion, IL



54c) Racine, WI



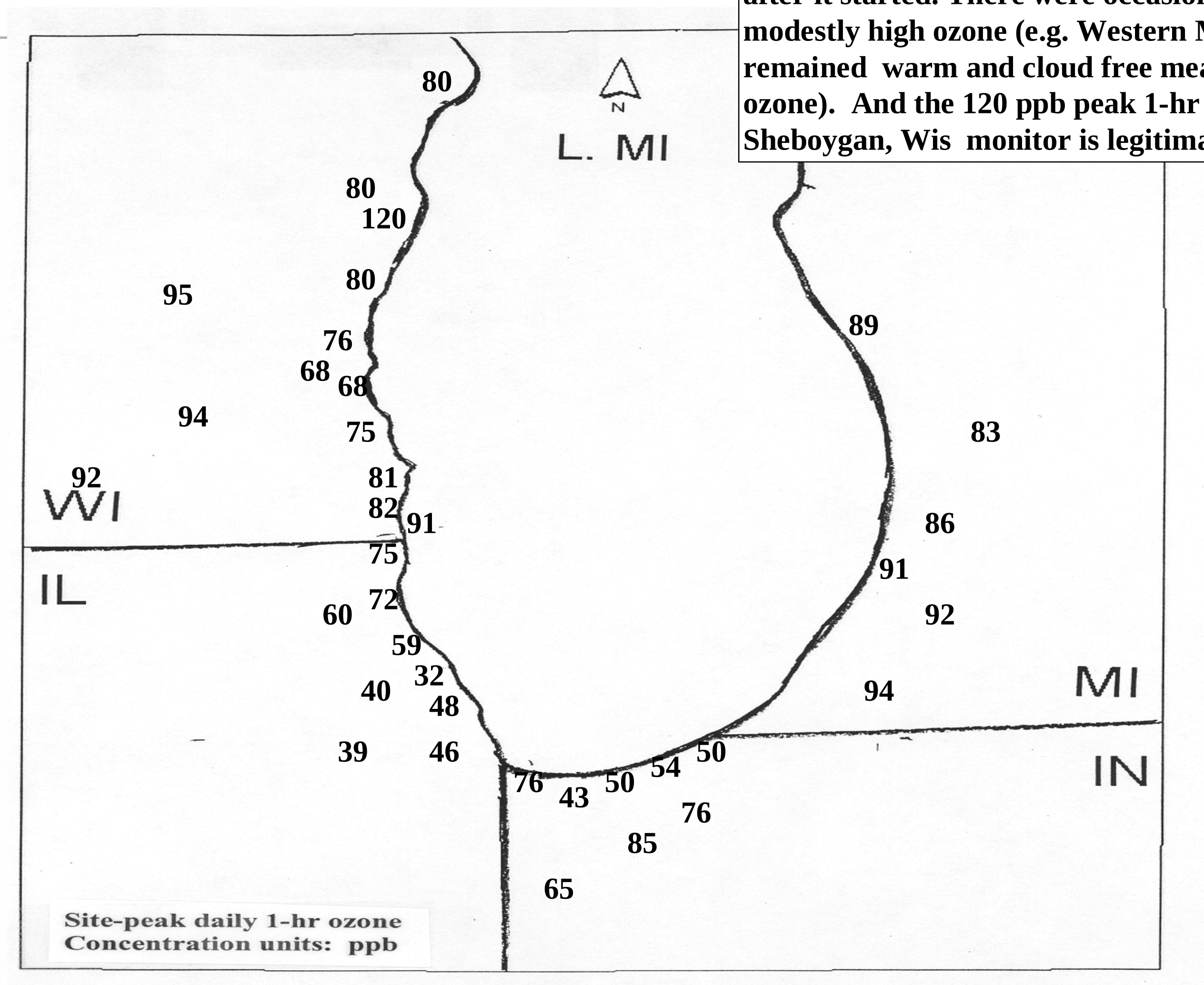
54d) S. Lake Mich Buoy



<u>6/25/02 surface</u>: Mich. City, Zion & Racine all encountered considerable cloud activity that was coming largely from the south (Fig. 44) on this day. Consequently, the substantial decrease in ozone was beyond the influence of the wind flow, which still hada strong southerly component -- which helped explain the 27-30 C temps at these sites on this day (in spite of the clouds). The Lake buoy again monitored mostly modest (3-5 m/s) SWly-to-SEly surface flow.

Figure 55
Site Peak-Daily 1-Hr Ozone (ppb)
Monitoring Sites in the S. Lake Mich. Area
25 June 02 (Tuesday)

<u>6/25/02 Peak surface ozone:</u> **The cloud cover that migrated northeastward into most of the southern Lake Michigan basin was a majorreasonthat this ozone episode came to a conclusion on 6/25, 4 days after it started. There were occasional spots of modestly high ozone (e.g. Western Mich, which remained warm and cloud free measured 90 ppb+ ozone). And the 120 ppb peak 1-hr ozone at the Sheboygan, Wis monitor is legitimate.**



Summary Conclusions (Page 1 of 9)

Ozone Episode
Southern Lake Michigan Region
20 - 25 June 02

- **During 21 - 24 June 02 the inter-related synoptic and Lake (mesoscale) meteorological features greatly enhanced the lower troposphere's capability to efficiently generate and transport very high ozone levels at certain coastal sites in the Southern Lake Michigan region. The ozone-conducive meteorological features, as viewed over land, included:**
  - **A cold front that stalled across southern L. Michigan on 21 June (Fig. 9), then evolved into a slowly-northward moving warm front during 6/22-6/24 (Fig. 12).**
  - **A persistent high pressure system across the northeastern USA (e.g., Fig. 24) -- advecting warm, humid, polluted air into the L. Michigan region south of the front.**
  - **This high pressure system was also responsible for large-scale subsidence in the region, causing both reduced atmospheric mixing / dilution of air pollutants and predominantly cloudless skies that allowed for increased solar radiation and heat (warmer temperatures) which enhance the photochemical production of ozone.**

Summary Conclusions (Page 2 of 9)

Ozone Episode
Southern Lake Michigan Region
20 - 25 June 02

- These ozone conducive weather conditions occurred during the calendar period that included the summer solstice in the northern hemisphere. These days of highest insolation during the year increased the amount of solar energy available for photochemically producing ozone.
- The high pressure system had a weak surface pressure gradient, which resulted in low surface wind speeds. This air stagnation allowed a buildup of, heat (warm temperatures), moisture, ozone and ozone precursors in the shallow mixing layer throughout the region, including over Lake Michigan during the episode.
- The morning land-based winds (Figs. 22, 31, 41) advected ozone and fresh ozone precursor emissions from both the Gary-Chicago-Milwaukee area and upwind regions eastward offshore to over L. MI.
- The clear skies (abundant solar radiation) with reasonably warm, humid, weak flow and mixing were ideal for optimizing photo-chemical processes to take place -- potentially transforming much of the precursors into ozone.

Summary Conclusions (Page 3 of 9)

Ozone Episode
Southern Lake Michigan Region
20 - 25 June 02

- A substantial difference in the afternoon surface temperatures between the land (warm) and Lake Mich. (cold) (Fig. 18) allowed a weak surface lake breeze circulation pattern to penetrate onshore along the southwestern and southern L. Mich. shoreline during the late morning / early afternoon of each day, 22-24 June (Figs. 22, 31, 41).
- The lake breeze onset during the late morning-to-afternoon period brought ozone-laden air back on-shore during this period for each day of 22 - 24 June (Figs. 22, 31, 41).
- The on-shore, ozone-laden lake breeze was relatively weak during this episode. It was only able to penetrate a few kilometers inland before succumbing to prevailing (synoptic) lakeward flow. This resulted in excessively high ozone being measured only at several near-shore sites in the S. Lake Mich. vicinity during the episode (Figs. 23, 32, 42).
- On 25 June the ozone episode ended due to the presence of strong convective activity (clouds, rain) associated with an non-frontal cloud mass that moved through the S. Lake Michigan region on that day.

Summary Conclusions (Page 4 of 9)

Ozone Episode
Southern Lake Michigan Region
20 - 25 June 02

- **During 22-25 June 02 -- ambient ozone and meteorological measurements were collected aboard a Wis DNR airplane over S. Lake Mich. -- as many as 4 flights per day (Figs 2 & 3). A contractor airplane (RB Jacko) monitored ozone and other parameters along the over-land region upwind (south & west) of L. Mich (Figs. 4 & 5). The WDNR aloft measurements show how meteorological fields over L. Mich. were often favorable to the formation and on-shore transport of O3 during this episode, as follows:**
  - **Warm temperatures (up to 28 C) over the Lake (at all levels) -- to help drive the thermal component of the photochemical processes.**
  - **There were early morning near-surface winds from land to lake (e.g., 6/24 Flight A [Fig 35d]). This flow transported ozone and fresh (rush hour) ozone precursor emissions towards the Lake.**
  - **A shallow conduction inversion was often observed just above the relatively cold Lake (e.g., Figs 35a & b). The inversion is a stable (subsiding), slightly humid but cloudless air mass that can serve to stabilize the precursor emissions transported into it (i.e., off-shore flow) and subject them to considerable sunlight exposure and heat for efficient photochemical transformation into ozone (Appendix A).**

Summary Conclusions (Page 5 of 9)

Ozone Episode
Southern Lake Michigan Region
20 - 25 June 02

- **The precursors' exposure to solar radiation for (photochemical processing) was particularly excessive during this ozone episode due to 1) cloudless, warm, stagnant synoptic conditions from a dominant high pressure system, and 2) the episode occurred during the northern hemisphere's summer solstice (longest daylight periods of the year).**
- **The consistently high ozone (e.g, Figs 19, 28, 38: up to 160 ppb) measured above the Lake was indicative of how active the over-Lake photochemical processes were during this episode.**
- **The near-surface wind directions would often reverse to being on-shore during later WDNR flights in the day (e.g., 35d). These eastward-moving flows, were carrying large amounts of newly-produced ozone towards land.**
- **When this landward-moving flow (with lots of ozone) was able to penetrate the coastline, then that area had witnessed a "lake breeze" (e.g., Figs. 22a, 22b and 22c).**

Summary Conclusions (Page 6 of 9)

Ozone Episode

Southern Lake Michigan Region

20 - 25 June 02

- **The strength of the ozone-laden lake breeze during this episode was apparently rather weak (Fig 43b). High ozone at the surface was restricted to those land-based sites near Lake Mich. (Figs 23, 32, 42).**
- **When the lake breeze impacts on land, the prevailing synoptic scale flow (usually with a westerly component) often travels up and over the conduction inversion layer / lake breeze (Appendix A). This land-based afternoon / night-time eastward flow, which often transports considerable amounts of ozone aloft over the Lake, was measured in all surface wind direction profiles (e.g., Fig. 22) and during all WDNR flights at 300 m above the Lake (e.g., Fig 15d).**
- **This eastward transported ozone aloft is often insulated from both deposition and destruction by the stable air mass over the Lake (Appendix A). Consequently, much of this aloft nocturnal ozone can be sustained and carried over to the next morning. Early morning ozone of 100 ppb+ was measured 300 m over the Lake on 6/23 (Fig. 25) and 6/24 (Fig. 34).**

Summary Conclusions (Page 7 of 9)

Ozone Episode
Southern Lake Michigan Region
20 - 25 June 02

- **It is possible that some of this carryover ozone could eventually sink (subside) under the combined synoptic high pressure-mesoscale high pressure over the Lake (Appendix A). This subsidence could extend into to the conduction layer, where might be expected to "fan out" towards the shoreline as part of the lake breeze.. There was no measurement data collected during this episode to evaluate this hypothesis.**
- **The RB Jacko L. Mich. boundary flights were over predominantly rural areas upwind of the Gary-Chicago-Milwaukee metro region (Figs. 3 & 4). Nevertheless, these mid-day flights monitored relatively high ozone (upwards of 100 ppb [Figs. 21, 30, 40]) that was somewhat uniformly distributed vertically, despite the plane's constant "dolphin" trajectory between 70 and 900 m above the ground. This indicates that synoptic-scale air masses that are stagnant, warm, mostly cloudless and hazy for several days have the potential to generate and transport large amounts of ozone in many areas of the upper midwest.**

Summary Conclusions (Page 8 of 9)

Ozone Episode

Southern Lake Michigan Region

20 - 25 June 02

- The meteorology of persistent synoptic high pressure in combination with summertime L. Mich. meteorology sometimes result in a very efficient photochemical reaction chamber and transport mechanism. This meteorologically-driven “photochemical production transport potential” in the Lake Michigan vicinity greatly exceeds that ozone potential for other areas in the midwest.
- On occasion (i.e., this ozone episode) -- this ozone formation / transport potential in the Lake Michigan area is realized, in part, due to considerable emissions from the large metropolitan areas next to the Lake. Air pollution transport from outside the region is also an important .
- The ozone episode of 20 - 25 June 02 in the southern Lake Michigan basin demonstrated this substantial potential of the region’s synoptic-Lake meteorology to support the production and transport of excessively high ozone -- resulting in 30 site-day exceedances of the 1-hr ozone NAAQS -- despite over 25 years of regulatory efforts to reduce the amount of ozone emission precursors, both regionally and nationally. Enough ozone 1-hr NAAQS exceedances to force WI, IL & IN to withdraw (at least temporarily) their request to redesignate fully to attainment of this standard.

Summary Conclusions (Page 9 of 9)

Ozone Episode

Southern Lake Michigan Region

20 - 25 June 02

- **Despite this air quality setback, the regulations enacted to reduce and control ozone precursor emissions have been very beneficial. Namely the duration, intensity and geographical extent of the meteorological conditions that made this episode possible were exceptionally great. A similar weather scenario would likely have resulted in much higher ozone, more ozone NAAQS exceedances over a wider geographical area in the region as recently as perhaps 7-10 years ago.**

- **Nevertheless, this episode demonstrates that more controls might still be necessary to reduce ambient ozone.**

Acknowledgments

- **To John Hillery & Dr. Robert Jacko for each planning, configuring and maintaining the WDNR and RB Jacko aircraft, respectively, as a reliable, effective platform for monitoring air pollutants and meteorological parameters aloft.**
- **To the WDNR pilots, Robert Jacko and all flight monitoring technicians who put in very long days and logged many hours aloft in order to collect the considerable amount of aircraft-based data.**
- **To John Hillery, Theresa Foley and Robert Jacko for reviewing, quality assuring, validating and formatting all of the aloft measurement data so that they would be available for analysis.**
- **To the State air monitoring staffs in Wisconsin, Illinois, Indiana and Michigan for collecting air pollution and meteorological measurement data at their aerometric monitoring sites in the general vicinity of Lake Michigan. And for their for reviewing, quality assuring, validating all of these data so that they also would be available for analysis.**

Appendix A
A Primer on Lake Breeze Meteorology

Throughout the discussion on the Lake Michigan ozone episode of 20 - 25 June 02, there were often references to terms such as "lake breeze" or "conduction inversion". These phenomena are important concepts in the explaining the meteorological processes that contributed to the production of such high ozone during this event.

The purpose of this appendix is to use portions of a reference to succinctly (and hopefully clearly) explain the scientific basis of the meteorology that greatly influenced this ozone episode. This information will hopefully give the reader a greater appreciation of the meteorological role in this episode.

These explanations come in the form of posting sections of the following published research: "*Lake and land breezes in southwestern Ontario: analyses and numerical modeling*" by Dr. David Sills. Ph.D dissertation, York University, Toronto, Ontario, 388 pp, 1998. The actual materials presented in this appendix were taken directly from Dr. Sills' web site (www.yorku.ca/pat/research/dsills/primer.html), which is entitled "A Lake and Land Breeze Primer".

The following text and figures are fully attributed to Dr. Sills' published research. Consequently, most of the text are taken directly from his work and accorded with quotation marks.

1) Introduction

“Atkinson writes that air over land expands more rapidly than air over water due to the warmer underlying surface during the day. Assuming that surface pressures over land and water are initially the same, this results in higher pressure over land than over water at constant heights above the surface causing air above the surface to flow offshore towards lower pressure during the day. This flow aloft induces a flow opposite in direction at the surface known as the 'sea breeze' or 'lake breeze'. “

“The intensity of the lake breeze circulation, as with all circulations that are thermally forced at the surface, is directly proportional to the magnitude of the horizontal temperature gradient and the depth of the temperature perturbation in the atmosphere. Thus, in the case of lake breezes, a greater temperature contrast between air over land and over water results in a more intense circulation.”

2) Synoptic Environments

"In order for local thermal forcing to predominate over synoptic-scale dynamics, the synoptic-scale pressure gradients must be relatively weak in the coastal region and clear to partly clear skies must be present so that insolation may heat the land surface. By definition, the air over the land surface must be warmer than air over the lake"

3) General Features

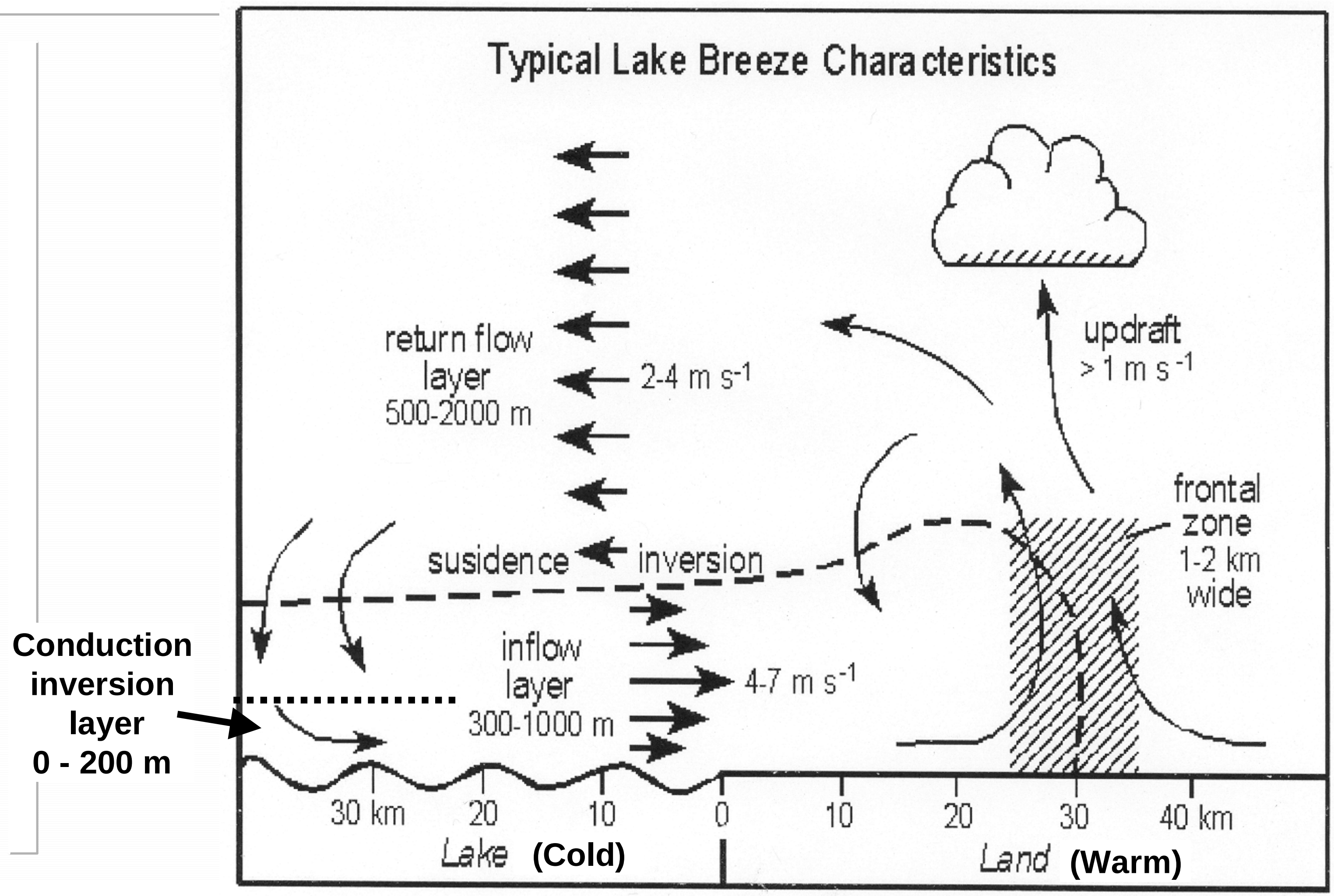
Along a straight coastline [As is mostly the case with Lake Michigan's western shoreline] in flat terrain, the lake breeze initially blows perpendicular to the shore, then may approach geostrophic balance (flow parallel to the shore) after a period of time due to the Coriolis acceleration if the circulation is long lived (Lyons, 1972). Lakes breezes, especially on the Great Lakes, become nearly as well-developed as their oceanic counterparts having a typical maximum inflow wind speed of 4-7 m s^{-1} and a slightly weaker typical maximum return current of 2-5 m s^{-1} aloft (Moroz, 1967; Lyons, 1972; Lyons and Olsson, 1973; Keen and Lyons, 1978). The maximum depth of a typical lake breeze inflow layer is between 500 m and 1000 m with the return current extending to 1000-2000 m above the inflow layer (Moroz, 1967; Lyons, 1972; Lyons and Olsson, 1973; Keen and Lyons, 1978). A typical lake breeze, based on observations from the literature cited here, is illustrated in Figure 2."

(Fig 2 -- see next slide)

"Typical [lake breeze] penetration distances [inland] for the Great Lakes region have been found to be near 30 km (Atkinson, 1981)." "Physick (1976) found by numerical simulation that for lakes roughly the size of the Great Lakes or smaller, circulations on each shore should not occur independently but interact to form a mesoscale high pressure area with associated subsidence over the water."

"The lake breeze circulation usually dissipates as changes in air temperature over land and over the lake eliminate the horizontal pressure gradient. This typically occurs near sunset. Lake breezes have also been observed to retreat to the shoreline due to an increase in cloud cover or increase in the offshore gradient wind (Ryznar and Touma, 1981)."

“Figure 2. Idealized illustration of a typical lake breeze circulation and its associated front based on the literature referred to in the thesis. Common features are labelled. The dashed line represents the outer boundary of the inflow layer. The frontal zone is not shown to scale.”



"Though lake breezes can occur any time of year as long as conditions for its development are met, they are most frequently observed in the spring and summer months. This is due to large lake-land temperature differences that typically occur in the spring and the prevalence of synoptic conditions conducive to lake breeze development during the mid-summer months.

Lyons (1972) reported the highest frequency of lake breeze occurrence in the late spring and summer months on the eastern and western shores of Lake Michigan over 10 warm-season months. Occurrences earlier and later in the year were fairly common and were recorded even in January and February."

4) Lake Breeze Fronts

"After the initial development of a lake breeze circulation, the leading edge of the lake breeze may begin to show many similarities in temperature, humidity, pressure and wind changes to a scaled-down synoptic-scale cold front. This occurs primarily by the tightening of horizontal gradients at the lake breeze convergence zone. Lyons (1972) found that shifts in wind direction are the best markers for inland lake breeze tracking. The rate of inland advance is highly dependent upon the gradient wind. However, lake breeze winds behind the front are usually greater than the propagation speed of the front. Thus, upward vertical motion occurs at the frontal convergence zone. Lyons and Olsson (1973) observed that the Lake Michigan lake breeze front was 1-2 km wide"

5) Land Breezes

"Land breezes have requirements for their formation similar to those for lake breezes: light winds associated with a weak pressure gradient, clear to partly clear skies, and a lake-land temperature gradient. The land breeze forms after sunset when radiational surface cooling commences. Since land surfaces cool more rapidly than water surfaces, air over land becomes cooler than air over water and begins to contract. The constant pressure surfaces over land shift downward through the depth of the atmosphere in response and the initiation process described for the lake breeze occurs, but in reverse. Thus, an offshore flow is generated near the surface while an onshore flow is induced aloft."

6) Air Pollution Effects

"Many studies have demonstrated the exacerbation of air pollution problems in coastal areas. Some of these effects are related specifically to mesoscale circulations such as lake and land breezes. A commonly occurring effect in coastal areas is plume trapping. Stably stratified marine air moving onshore can have a mean mixing depth that is 10% of that existing away from the influence of the lake (Lyons and Cole, 1973). Thus, effluent that is ejected into this layer is effectively trapped and high concentrations of pollutants can subsequently reach the surface.

Lake and land breezes can introduce unique problems. The first is the ability of lake and land breezes to transport pollutants in three dimensions. Lake and land breezes are quasi-closed circulations and pollutants emitted into them can be recirculated several times over the near-shore area (Lyons, 1972). That is, pollutants emitted into the inflow layer get lofted in the frontal regions and disperse into the return flow aloft. A fraction of these pollutants are forced into the inflow layer again by the descending branch of the circulation. Remaining pollutants reside in an elevated layer aloft."

“Another effect on air pollution peculiar to lake breezes involves the enhanced production of ground-level ozone or ’photochemical smog’. The ingredients for enhanced ground-level ozone concentrations include: a plentiful supply of reactive hydrocarbons (RHC) and nitrogen oxides (NO_X), strong insolation, relatively high air temperatures, light wind speeds and limited mixing depths (Lyons and Cole, 1976). Three of these ingredients - strong insolation, high temperatures and light winds - are also conditions conducive to the development of lake breezes. When a lake breeze occurs, enhanced insolation is common over the lake and at inland locations affected by the circulation and can result in increased ozone production there.

Thus, the occurrence of high concentrations of pollutants, especially ground-level ozone, in coastal regions is highly correlated with the occurrence of lake and sea breezes and, to a lesser extent, land breezes.“